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# FULL-SCALE STUDY OF PLUME RISE AT LARGE ELECTRIC GENERATING STATIONS

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# FULL-SCALE STUDY OF PLUME RISE AT LARGE ELECTRIC GENERATING STATIONS

Muscle Shoals, Alabama

September 1968

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## SUMMARY

Improved capability for estimating plume rise is needed for more accurate and confident assessment of diffusion problems. In 1963 the Tennessee Valley Authority under sponsorship of the Public Health Service initiated a comprehensive plume rise study at its generating stations. Plume rise data were collected at six coal-fired, steam-electric generating stations. Unit ratings ranged from 173 to 704 megawatts with stack heights varying from 76.2 to 182.9 meters.

An instrumented helicopter and special photographic equipment were used to obtain 1,580 separate plume observations and values of significant meteorological parameters during stable, neutral, and slightly unstable conditions. The 1,580 observations were resolved and consolidated into 133 composite observation periods covering 30 to 120 minutes.

The data were evaluated in respect to six plume rise formulas in general use: Holland; Bosanquet; Davidson-Bryant; Csanady; CONCAWE; and Lucas, Moore, and Spurr. The CONCAWE formula showed best agreement with observations. Analysis of data indicates that, of all the variable quantities in the formulas, wind speed and heat emission rate are the principal determinants of plume rise. Three of the formulas (Csanady; CONCAWE; and Lucas, Moore, and Spurr) were modified for optimum agreement with observations. The optimized CONCAWE and Csanady formulas are judged to provide estimates of plume rise which meet practical requirements in diffusion calculations. The optimized Csanady formula takes account of the relatively minor variation of plume rise with stability and is therefore

preferable for closer accuracy. However, its use requires information on meteorological parameters which is often not available. The more simple CONCAWE formula which requires information only on heat emission rate and wind speed may therefore be preferable for general use.

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# FULL-SCALE STUDY OF PLUME RISE AT LARGE ELECTRIC GENERATING STATIONS*

## INTRODUCTION

Since the early fifties the Tennessee Valley Authority has had an increasing interest in studying the rise of hot smoke plumes from its large power plants in relation to the dispersion of atmospheric effluents. Studies have progressively shown the need for more information on plume rise and related meteorological parameters if satisfactory resolution of plume dispersion is to be achieved. Special studies by TVA as well as by other groups have provided sufficiently accurate diffusion parameters and coefficients to describe, in most cases, rates of dispersion for principal meteorological dispersion models. However, in order to apply this information to practical diffusion problems, effective stack heights must be known. A number of plume rise formulas derived primarily from data on small stack emissions are in popular use. Application of these formulas to increasingly larger emission sources warrants a closer examination of their conformity with actual experience.

## EARLY STUDIES

In 1951 TVA initiated plume rise studies by making observations at the Watts Bar generating station which had four 60-megawatt units served by two stacks extending 150 feet aboveground or 50 feet above the main building. Plume rise data were collected by a simple perspex grid device operated on a planetable at an established observation point. In the midfifties a special

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*Report prepared by S. B. Carpenter, Supervisor, Air Quality Studies Section; Fred W. Thomas, Chief, Industrial and Air Hygiene Branch; and F. E. Gartrell, Assistant Director of Health, Tennessee Valley Authority.

peep sight and cross wire were adapted to a standard transit to obtain greater plume coverage as well as improved accuracy. This instrument was used to collect plume rise data at the Johnsonville, Shawnee, and Kingston stations with generating capacities ranging from 750 to 1,500 megawatts and stack heights from 170 to 300 feet. Data from these field observations were very helpful in extrapolation of plume dispersion from the smaller stations to the larger new stations. However, classification of these plume rise data according to principal diffusion models was not clearly established since the supporting meteorological data were collected from relatively low tower installations and did not necessarily represent ambient meteorological conditions at the higher plume elevations.

Improved plume rise information[1] was collected during the 5-year (1957-1962) research project titled "Full-Scale Study of Dispersion of Stack Gases" conducted by TVA under sponsorship of the Public Health Service. For the first time in TVA's experience, plume rise data were obtained along with meteorological parameters, i.e., wind direction and wind speed profiles and vertical temperature gradient, representative of the plume environment. This limited information obtained on plume rise was incidental to the principal study of plume dispersion.

## CURRENT STUDIES

To meet a growing need for reliable and comprehensive plume rise data from large industrial-type stack emissions, TVA, under sponsorship of PHS, initiated in 1963 a special 3-year research project titled "Full-Scale Study of Plume Rise at Large Electric Generating Stations." The study was particularly timely because experience, techniques, and special equipment developed in the preceding 5-year dispersion study were directly applicable.

Also, the variability of available plant sizes, stack heights, and stack configurations accommodated full-sca'e assessment of plume rise over a wide range of conditions. Valuable assistance and guidance were provided by R. A. McCormick and Bruce Turner, Air Resources Field Research Office, National Air Pollution Control Administration, PHS.

## Basic Workplan

The objective of this study was to collect, compile, and analyze data for documentation and definition of plume rise and related meteorological parameters at a range of generating plants. Six generating plants were chosen for the study with unit ratings from 173 to 704 megawatts and stack heights from 76.2 to 182.9 meters.

The first two years of the study, completed in the spring of 1965, were devoted primarily to collection of field plume rise and meteorological data at the six steam plant sites. Fieldwork was scheduled in seasons of the year when frequencies of desired meteorological regimes were expected to be the highest, i.e., high winds and neutral stability in the spring (March-April) and low winds and stable or inversion conditions in the fall (September-October). A third regime, i.e., low winds and unstable conditions, was also documented whenever possible. Procedural aspects of the study were presented in an interim report[2] at Toronto, Ontario, Canada.

## Data Compilations

A comprehensive data collection program was devised. The three general categories of data included (1) plant design and operational factors, (2) meteorological information, and (3) plume profile, elevation of plume top and bottom.

## Plant Design and Operational Factors

Principal plant design and operational factors for the six steam plants are shown in table 1. Operational data kept at the generating plants were available for the study. For each field study period the amount and analysis of coal burned for each unit and the unit level of operation were obtained for determination of stack effluent velocity and heat emission rate. Precise stack gas temperatures at the stack outlet were also obtained from a special sampling program developed for the study and carried out by TVA's Division of Power Production.

## Meteorological Information

Wind direction, wind speed, and temperature profile data were collected routinely. Wind profile data were obtained at approximate 20-minute intervals by double-theodolite technique using standard Warren-Knight Model No. 85 theodolites positioned at the ends of 1,000- to 1,500-foot baselines. Several baselines were established at each plant site to ensure good angular separation between simultaneous instrument readings for a wide range of wind directions. Standard U. S. Weather Bureau-type, helium-filled, 10-gram sounding balloons were used throughout the study and provided a suitable ascension rate, i.e., approximately 500 feet per minute throughout the 3,000- to 5,000-foot observational layer. The use of a balanced balloon also permitted single-theodolite operation in the event the secondary station lost the balloon in flight or experienced instrument or communication malfunction. Communication between the two theodolite stations was by two Cadre Model C-75 all-transistor, 2-way, battery-operated radios. A Warren-Knight Model No. 485 timer located at the primary station (balloon release point) provided the 30-second time signals. Theodolite readings were recorded on an AC-operated portable

Audograph at the primary station and on a DC-operated portable Audograph at the secondary station. Figure 1 illustrates instrumentation used at a primary pibal station.

Vertical temperature profiles were obtained from a Bell Model 47-D-1 helicopter equipped with a Cole-Parmer Model 8425 temperature indicator. Profile runs were made at 45-minute intervals in the immediate plume area about one mile from the power plant. Individual readings were taken at 100-foot intervals from surface to about 500 feet above the plume top.

Additional meteorological information, i.e., surface wind direction, wind speed, and dry-bulb and wet-bulb temperatures, was recorded before each pibal release at the primary station. Also, cloud coverage and other pertinent meteorological or plume observational information was recorded.

General synoptic weather information from U. S. Weather Bureau radiosonde observations and surface and upper air charts was also compiled for analysis and evaluation.

## Plume Profile

The objective of this phase of data collection was to define the plume profile for various combinations of generating unit sizes, stack heights, and meteorological conditions. Three separate simultaneous field measurement techniques were used--ground level photography, ground level modified transit readings, and helicopter observations. Ground photography was the principal source of data.

The three replicate plume profile measurement techniques were designed to provide verification of data and to permit evaluation of the several measurement techniques.

Photographic Technique--A 4- by 5-inch Super Graphic camera was mounted on a modified transit head. The focal points for both the 135-mm

and telephoto lens were aligned to coincide with the vertical axis of the tripod mount to provide accurate angular plume coverage. The assembly is shown in figure 2. The camera was located at one of several referenced sites, usually one to two miles from the power plant where right angular orientation to the plume path, along with favorable light exposure, could be maintained. The 135-mm lens with a horizontal field of 42 degrees was used at sites from one to one and one-half miles from the source. The telephoto lens with a field of 16 degrees was used when the sites were about two miles distant. When the plume was near perpendicular to the camera line of sight, approximately six-tenths to one mile of the plume segment could be photographed.

During the first two years of field study, about 1,500 plume rise photographs were taken. Experimentation with various film types, camera settings, etc., led to adoption at the end of the first year of a standard photographic procedure consisting of 1-second instantaneous and 1.8-minute, time-exposed infrared photographs taken alternately at 5-minute intervals. Infrared film provided superior plume delineation in most cases and was used in preference to standard black-and-white or Polaroid film types. Excellent quality control was also attained with infrared film. For all daylight infrared exposures, an f/32 aperture was used. The 1-second instantaneous exposures required an infrared Wratten A filter. The 1.8-minute time exposure required an infrared Wratten A filter and a 1-percent neutral density filter.

Transit Survey Technique--Plume profile measurements were also taken simultaneously by a modified transit located a few feet from the camera. Figure 3 shows the general plan for plume observation. Observations were made from an established surface location to the top and bottom

of the plume at 10, 20, 30, 40, and 50 degrees horizontal from a selected reference stack.

Helicopter Observation Technique--Elevation of top and bottom of the plume was also recorded about every 45 minutes at one-half and one mile and at two miles when possible by visual observation and helicopter altimeter readings. The helicopter was also used during each study period to maintain continuous surveillance on the direction of plume travel. These observations were obtained by references to established ground control points.

## Scope of Fieldwork - Data Collection

Fieldwork was conducted on 50 days totaling about 311 hours of actual field sampling. Data included 1,580 plume photographs, 494 double- and single-theodolite pilot balloon runs, and 305 helicopter temperature profile runs; total helicopter time was 188 hours.

## Data Processing and Tabulation

All data from photographs, pilot balloon observations, and temperature soundings were programmed for computer analysis and graphic display. Plume profile data from photographs were resolved by means of special template overlays constructed for the respective lens type. The template was designed to provide horizontal and vertical angular values on all segments of the plume. Horizontal and vertical angle readings from plume photographs were established with reference to horizontal and vertical angles of the center of the photograph and the fixed point at the top of the reference stack. Spot checks made on selected segments of the plume showed them in close agreement with readings obtained with the transit. With concurrent plume directional information obtained through observations

from the helicopter, these data were processed through the computer for final resolution of the plume profile. Elevation of plume top and bottom observed from the helicopter agreed closely with corresponding points on the plume profile obtained from the photographs.

Figure 4 illustrates the manner in which the template is superimposed on a plume photograph preparatory to analysis. Each of the curved horizontal and vertical grid lines represents 2 degrees. Curvature of the lines compensates for image distortion resulting from curvature of the camera lens. At the time of this photograph, the camera lens centerline was positioned 20 degrees horizontal and 8 degrees vertical from the reference point at the top of the upwind reference stack. The vertical angle to top of the reference stack is 7.9 degrees. The overlay template is superimposed on the plume photograph with the centerline elevation reading of 8 degrees aligned along the center of the photograph. Note that the 20-degree horizontal line of the template coincides with the top of the upwind referenced stack. The sign at the center portion of the figure displays code numbers necessary to identify each photograph.

For each series of photographs the mean height of top and bottom of the plume was determined as a function of distance from the plant; and from these values a plot of the centerline position was derived, the centerline being defined as the arithmetic mean between the top and the bottom. From these plots, rise of the centerline as a function of distance was determined. Figure 5 illustrates a portion of the April 1 field data, including the plume photograph taken at 0715, along with concurrent wind and temperature profiles and computer-resolved plume profile plots.

Detailed data obtained on plant operation, wind speed and wind direction profiles, temperature profiles, plume profiles from photographs,

and other related data are not tabulated in this report but are available from the files on request.

The 1,580 separate plume rise observations taken at 5-minute intervals at the six plants were consolidated into 133 composite observations,[3] table 2, each covering time periods of 30 to 120 minutes. Duration of composite periods was determined by the constancy of principal meteorological and operational parameters. Therefore each of the data points represents from six to twenty-four 5-minute consecutive observations.

Data in table 2, the 133 composite observations, were next classified into the following stability ranges based on the temperature gradient from stack top to plume top.

| | | Group |
|---|---|---|
| Inversion, | $\frac{\Delta\theta}{\Delta z} > 1.00°\,K/100$ meters | 1 |
| Stable, | $0 < \frac{\Delta\theta}{\Delta z} \leq 1.00$ | 2 |
| Neutral and Unstable, | $\frac{\Delta\theta}{\Delta z} \leq 0$ | 3 |

These classifications, along with heat emission rate, flue gas exit velocity, and average wind speed from stack top to plume top, for single stack operation are shown in table 3. The average plume rise for wind speeds in selected ranges for each stability group was also developed in this table.

## Data Analysis and Evaluation

### Point of Effective Plume Rise

Often the most difficult point to establish from a plume profile is the height at which the rise attributable to buoyancy and momentum terminates. A plume ascending and dispersing in neutral or unstable conditions will continue to expand vertically because of turbulent diffusion

after its momentum and buoyancy are spent. A number of procedures have been used by other investigators to establish the plume height resulting from plume buoyancy and momentum. In this study a relatively simple procedure, considered to be quite realistic, was evolved. This procedure, presented in a paper[4] coauthored by TVA investigators and Maynard E. Smith and John A. Frizzola, Meteorology Section, Brookhaven National Laboratory, was based on preliminary results of limited analyses of these data. Plume rise, $\Delta h$, was defined as elevation of the plume at the point in distance and space where rise of the plume centerline as a function of distance reached a minimum value or became constant. The plume often continued to ascend beyond this point. With this criterion, effective termination of plume rise occurred 457 to 1,219 meters from the source. In most instances observations extended well beyond this point.

In addition to a definition of criteria for establishing plume rise, it is desirable to determine whether one is observing the initial phase where source effects and mean winds are important or the final phase where the centerline asymptotically reaches a final height under the influence of atmospheric turbulence and stability. Difference in semantics and interests on these questions probably accounts for a large portion of the differences in plume rise reported by investigators. The data may be examined in respect to the initial plume rise phase in accordance with relation set out by Csanady[5] who defines the initial flux due to buoyancy and momentum as:

$$F = g\, V_s r^2\, \frac{\Delta T}{T}$$

where

$g$ = acceleration due to gravity (meters per second$^2$)

$V_s$ = stack gas exit velocity (meters per second)

r = stack exit radius (meters)

$\Delta T$ = temperature difference between exit stack gas and ambient air (°K)

T = ambient air temperature (°K)

If this flux, F, is divided by the cube of the wind speed, $\bar{u}^3$, a length, $\ell = \frac{F}{\bar{u}^3}$, is obtained. Then by dimensional analysis the distance variables may be made nondimensional:

$$\frac{z}{\ell} = \text{a function of } \frac{x}{\ell}$$

where z is plume rise and x is distance downwind. At the point $\frac{x_1}{\ell}$ where the plume levels off, the value of $\frac{z}{\ell}$ becomes constant. Values of $\frac{z}{\ell}$ and $\frac{x}{\ell}$, table 4, calculated for average plume rise at distances given in table 3, are plotted in figure 6. Because of the large number of points in figure 6, it is difficult to note the near constant $\frac{x}{\ell}$ values at the limit of the plume observation. The actual values of $\frac{z}{\ell}$ near maximum x distances may be noted in table 4. The leveling at the limit of plume observation can be seen more clearly in figure 7 where only 10 of the 27 groups in figure 6 are plotted. The $\frac{z}{\ell}$ and $\frac{x}{\ell}$ values at the end of the initial plume rise for the 27 summary observations listed in table 3 are plotted in figure 8. Here a two-thirds slope, as observed by others, fits the data quite well. The data are therefore considered representative of a close approximation of the end of the initial plume rise phase.

Compilation - Estimates of Quantities for Plume Rise Calculations

In table 5 either direct measurements or reliable estimates of every quantity needed for computation of plume rise according to all principal formulas now in use are compiled for each of the 133 composite observations along with observed plume rise. These include:

$V_s$ - stack gas exit velocity (meters per second)

$\bar{u}_4$ - mean horizontal wind speed at stack top (meters per second)

$\bar{u}_3$ - mean horizontal wind speed at plume bottom (meters per second)

$\bar{u}_2$ - mean horizontal wind speed at plume top (meters per second)

$\bar{u}_1$ - mean horizontal wind speed at plume centerline (meters per second)

$\bar{u}$ - mean horizontal wind speed between stack top and plume top (meters per second)

$\frac{\Delta\theta}{\Delta z}$ - change of potential temperature with height (°K per 100 meters)

$\Delta T$ - temperature difference between exit stack gas and ambient air (°K)

$T_1$ - temperature at which density of flue gases is equal to that of the atmosphere (°K)

$Q_H$ - heat emission per stack (calories per second), sensible heat

$Q$ - stack gas emission rate converted to temperature, $T_1$ (meters$^3$ per second)

$\Delta h$ - observed plume rise above top of stack (meters)

$\theta$ - plume angle off the line of stacks (degrees)

Range of Plant Operation and Meteorological Conditions Covered

The range of principal plant operational and meteorological conditions spanned by these observations is summarized as follows.

| | |
|---|---|
| Stack gas velocity | 7.7 to 29.2 meters per second |
| Volume emission rate | 1.36 to 6.63 meters$^3$ per second x $10^2$ |
| Stack gas temperature | 106 to 145° C. |
| Heat emission rate | 0.528 to 2.46 calories per second x $10^7$ |
| Wind speed, $\bar{u}$ | 1.0 to 16.8 meters per second |
| Ambient temperature | 273 to 304° K |
| Potential temperature gradient | -0.53 to 3.74° K per 100 meters |

The range and relation of volume emission to heat emission are shown in figure 9.

## Wind Speed Relationships

Because of the predominant effect of wind speed on plume rise, wind speed relationships were examined in some detail. Average wind speed occurring between stack top and plume top is plotted in figure 10 against the potential temperature gradient between the same two points. Most of the observations fall within a 1- to 12-meter-per-second wind speed covering a potential temperature gradient ranging from -0.5 to 3.7° K per 100 meters. Average wind speed measured at stack top is in most cases slightly less than average wind speed occurring between stack top and plume top, figure 11. Plume rise from single stack operation when associated with average wind speed observed at stack top, figure 12, shows a slightly greater spread than when associated with average wind speed between stack top and plume top, figure 13. Therefore the average wind speeds as observed between stack top and plume top were used throughout this analysis unless otherwise indicated.

## Comparison Between Observed and Calculated $\Delta h$ Values from Principal Plume Rise Formulas

The observed plume rise was examined with respect to fit with principal existing plume rise formulas. Formulas selected for comparison were Holland;[6] Bosanquet;[7] Davidson-Bryant;[8] Csanady;[5] CONCAWE;[9] and Lucas, Moore, and Spurr.[10] In each case the formula has been applied as recommended by the author without benefit of adjustment factors suggested by later investigators. The formulas used, together with complete description of the various parameters, are given in appendix C. Calculated plume rise using the various formulas is given in table 6 and plotted against observed values for single stack operations, table 5, in figures 14-19. In these plots points are coded according to wind speeds equal to or less than 3 meters per second and greater than 3 meters per second.

The relation of observed plume rise with calculated plume rise shown by the various formulas is as follows:

1. Holland formula, figure 14, shows fairly good agreement with a tendency to slightly underestimate plume rise.
2. Bosanquet formula, figure 15, overestimates plume rise and induces large scatter.
3. Davidson-Bryant formula, figure 16, seriously underestimates plume rise.
4. Csanady formula, figure 17, shows good agreement for wind speed equal to or greater than 10 meters per second. However, it overestimates the plume rise for wind speeds less than 10 meters per second; and the points for wind speeds less than 5 meters per second fell off the plot or exceeded the ordinate scale.
5. CONCAWE formula, figure 18, shows good agreement.
6. Lucas, Moore, and Spurr formula, figure 19, has a tendency to overestimate the plume rise and induce large scatter.

Individual points shown in these plots represent specific observations averaged over periods when some variability in meteorological parameters was inevitable and some fluctuation would normally be expected in the results.

## Optimization of Formulas Based on Observed Plume Rise

On the basis of relationships shown in table 6 where observed and calculated plume rise values are listed and in figures 14-19 where these values are plotted, three of the six plume rise formulas were selected for optimization by the process of multiple regression for best conformance with the plume rise values observed in this extensive study. In this process the basic elements of each formula were retained, but coefficients and exponents

were modified to yield best agreement with observations. Fit of the basic formula with observed values, amenability to the regression technique, and inclusion of significant meteorological parameters were the basis of this selection. In optimizing these three formulas, only observations where analyses indicated that full rise had been attained were considered; thus the optimization was based on the 27 summary observations listed in table 3 according to wind speed and stability classification.

The Csanady formula with the $\bar{u}^3$ term in the denominator is obviously not useful with low to moderate wind speeds. However, it was selected for optimization because it predicts a linear dimension and contains the significant meteorological parameters required for evaluating the effect of ambient conditions, especially stability. The simple CONCAWE formula was selected because of its superior agreement with observations. The Lucas, Moore, and Spurr formula was selected because of its adaptability to optimization. It is considered that optimization of these formulas over the broad range of plant designs, operational factors, and meteorological conditions encompassed in this study should either confirm the efficacy of the formula as initially presented or result in some improvement for application to large power plants.

The equations for the optimized Csanady; CONCAWE; and Lucas, Moore, and Spurr formulas are listed in appendix C.

When programmed for optimization the original Csanady formula

$$\Delta h = 250 \frac{F}{\bar{u}^3}$$

became

$$\Delta h = 133\left(\frac{F}{\bar{u}^3}\right)^{.27}$$

for the full range of stability conditions.

Data falling into each of the three stability classes were then reprogrammed using the following formula

$$\Delta h = C\left(\frac{F}{\bar{u}^3}\right)^{.27}$$

from which the following values of C were determined:

Stability class 1 (0.013° K per meter, average potential temperature gradient) = 119

Stability class 2 (0.003° K per meter, average potential temperature gradient) = 131

Stability class 3 (-0.0006° K per meter, average potential temperature gradient) = 137

These values of C plotted against the potential temperature gradient, appendix C, show a straight-line relationship, that is, the coefficient C becomes larger as the potential temperature gradient decreases.

Utilizing the final formula with the appropriate C values, the values of $\Delta h$ were calculated and are plotted against observations in figure 20. As shown by this plot the optimized formula reduced the scatter considerably from that shown in figure 17 when using the original formula.

The original CONCAWE formula derived by multiple regression from observations of Rauch[11] in Europe showed very good agreement with observations at TVA steam plants, figure 18. The original CONCAWE formula makes no provision for difference in atmospheric stability and as stated by the author is applicable to neutral and near-neutral conditions. When this formula

$$\Delta h = 0.175\left[\frac{Q_H^{1/2}}{\bar{u}^{3/4}}\right]$$

was optimized for best conformity with TVA data, it took the form

$$\Delta h = 0.414 \left[ \frac{Q_H^{.444}}{\bar{u}^{.634}} \right]$$

While the apparent fit with TVA data was not significantly improved, figure 21, optimization did result in slightly better agreement for particular points.

The Lucas, Moore, and Spurr formulas

$$\Delta h = \frac{0.7\ \alpha_N}{\bar{u}} \left[ \frac{Q_N}{G_N} \right]^{1/4} \text{ for stable conditions}$$

and

$$\Delta h = \alpha_N \left[ \frac{Q_N^{1/4}}{\bar{u}} \right] \text{ for neutral or slightly unstable conditions}$$

were adjusted by regression analysis to fit the data from single stack operation. Two regression analyses were made: (1) by holding the stack height factor $\alpha_N$ constant and solving for the exponent and (2) by holding the exponent constant and solving for the stack height factor $\alpha_N$. The calculated plume rise from both (1) and (2) gave approximately the same values; however, there is slightly less spread shown when holding the stack height factor $\alpha_N$ constant which gave

$$\Delta h = \frac{0.7\ \alpha_N}{\bar{u}} \left[ \frac{Q_N}{G_N} \right]^{.22} \text{ for stable conditions}$$

and

$$\Delta h = \alpha_N \frac{Q_N^{.20}}{\bar{u}} \text{ for neutral or slightly unstable conditions.}$$

The values of $\Delta h$ calculated from this optimized Lucas, Moore, and Spurr formula are plotted in figure 22 against the observed values. As shown by this plot there is a wide scatter; however, optimization reduced the spread somewhat from that shown in figure 19 when using the original formula. The

relation of the original formulas to the optimized forms is illustrated in figure 23 for the Csanady formula, in figure 24 for the CONCAWE formula, and in figure 25 for the Lucas, Moore, and Spurr formula where values calculated by both forms of these formulas are plotted.

Values of plume rise based on the three optimized formulas, along with observed plume rise values, are shown in table 7. In table 8 the values are classed in three stability categories (inversion, stable, and neutral and unstable) and in two wind speed ranges (equal to or less than 3 meters per second and greater than 3 meters per second). The range of calculated values in each category in relation to observed values is shown. From this summary table it can be seen that values for the optimized CONCAWE and Csanady formulas are comparable. The average of all calculations for the CONCAWE formula is 105 percent of observed and 106 percent for the Csanady formula. Greater variability is indicated for the Lucas, Moore, and Spurr formula where the average of all calculated values is 117 percent of the observed values.

Plume Rise When More Than One Stack is Operating

When more than one stack is operating, plume rise varies with plume direction off the line of stacks. Minimum rise occurs when the plume is 90 degrees off the line of stacks, and maximum rise occurs when the plume direction is along the line of stacks. Of the plume rise observations, table 5, 62 observations, or 47 percent, were obtained from a 2- to 9-stack operation with stack spacing ranging from a minimum of 25.2 meters to a maximum of 77.4 meters.

The optimized Csanady formula

$$\Delta h = C\left(\frac{F}{u^3}\right)^{.27}$$

shows an increase in plume rise of 22 percent with the addition of a second unit to the same stack when maintaining the same stack gas velocity. Therefore the plume rise would be increased by the following factor:

$$.22\ C\left(\frac{F}{\bar{u}^3}\right)^{.27}$$

If two stacks are used, one for each unit, the above factor would become smaller depending on the spacing between the stacks and the plume direction off the line of stacks. The above factor would become

$$\Delta h \text{ (increase)} = .22\ B\ C\left(\frac{F}{\bar{u}^3}\right)^{.27} (n-1)\ \text{Cos}\ \theta$$

where

n = number of stacks

$\theta$ = plume angle off the line of stacks

B = a value ranging from 1 at zero stack spacing to 0 at an approximately 3,000-foot stack spacing

On the basis of observations in this study, maximum initial plume rise was usually attained about 3,000 feet from the point of emission. Thus as a first approximation the assumption is made that a plume from stacks spaced 3,000 feet would not rise higher because of the second plume. However, as the spacing of stacks is made less than 3,000 feet and as the number of inline stacks is increased, an increase in plume rise does occur when the travel is in line with the stacks. The effect on plume rise of multiple stacks diminishes as the angle from the line of stacks increases and is minimal when the plume direction is normal to the line of stacks. Analysis of data from this and other related studies indicates that the term B, a coefficient related to stack spacing, is approximated by the values plotted in figure 26. On the basis of this relationship, the

incremental plume rise attributable to multiple inline stacks as calculated by the optimized CONCAWE formula would be

$$\Delta h \text{ (increase)} = .22 \text{ B } 0.414 \left[ \frac{Q_H^{.444}}{u^{.694}} \right] (n-1) \text{ Cos } \theta$$

Calculated $\Delta h$ values when two or more stacks were in operation, table 5, using the optimized Csanady and CONCAWE formulas are given in table 9 along with the observed $\Delta h$ values. Calculated values plotted in figures 27 and 28 against observed values show rather good agreement for wind speeds greater than 3 meters per second. For lower wind velocities the scatter is greater than that for comparable single stack operation in figures 20 and 21. The calculated values for both the single and multiple stack operations are plotted against observed values in figure 29.

Application of this empirically derived relationship for estimating the increase in plume rise attributable to inline stacks to practical problems and experience indicates that it has considerable validity in the range of our experience. Obviously, it results in appreciable increase in plume rise for a line of stacks, say 8-10, when the plume travels in line with the stacks. This would result in a significant reduction in concentration were it not compensated by the much smaller spread of the plume under such conditions. As a practical matter extensive monitoring at many TVA plants has indicated that the level of the maximum ground level concentration from multiple stack plants is closely comparable for all wind directions. We estimate that this empirical relation provides a reasonably sound basis for treating modern large generating stations which are unlikely to have more than four inline stacks. If stacks for such a plant were spaced 200 feet, the maximum plume rise increment over that of a single stack would be only 22 percent.

# CONCLUSIONS

Several of the semi-empirical plume rise formulas in current use were derived from data or observations on relatively small sources. Frequently, these formulas are applied to sources which are of a different order of magnitude from those on which they were initially based. Extrapolation of the relations inherent in these formulas may lead to significant errors in estimates of stack height requirements and pollution levels.

A comprehensive investigation of plume rise from large modern plants was therefore undertaken to establish the principal determinant factors and to strengthen the degree of confidence now afforded in estimates of diffusion by available formulas and procedures. Plume rise observations were made for units with capacities of 173 to 704 megawatts and stacks from 76.2 to 182.9 meters high. Observations were made over a relatively wide range of weather conditions. Also, direct measurements were made of significant meteorological parameters at the time of the observations. Analysis of data indicated that most observations extended to the point of maximum plume rise attributable to effluent forces such as velocity and buoyancy.

Preliminary results of limited analyses of these data were presented in an earlier paper.[4] However, study and analyses of the plume rise data have continued since that time and a more complete assessment is now possible. Plume rise data plotted against calculated values according to six formulas in general use indicated that of all terms in all formulas the wind speed and heat emission rate are the principal determinants. When plume rise observations were plotted against calculated values according to the formulas as originally presented by the author, the simple CONCAWE formula provided the best fit. Of the three formulas optimized to give best fit with TVA observations, both the CONCAWE and Csanady formulas were good.

Because of the simplicity and ease of calculation, use of the CONCAWE formula is considered preferable for general investigations. When a particular event such as an inversion breakup or limited mixing layer fumigation is being analyzed, use of the optimized Csanady formula is considered preferable, provided information is available on the meteorological parameters in this formula. This linear dimensional formula embodies the principal physical quantities normally associated with rise of a plume and permits some accounting for up to 15-percent difference in plume rise attributable to variation in atmospheric stability.

In conclusion, the study served to validate two plume rise formulas which can be used effectively over a range of meteorological and operational conditions. Plotting of the observed and calculated values shows some scatter even for the two best formulas. However, the scatter is limited and is equally distributed about a line of best fit. We doubt that the scatter can be reduced unless wind speed profiles are taken at less than 30-minute intervals and related to shorter observation periods, say 5-10 minutes. However, it is unlikely that even a reduction in scatter would result in any substantive change in the formulas that have been developed. The common agreement of the original CONCAWE formula derived by regression analysis from several hundred observations in western Europe with the TVA observations is judged to lend strength to this simple formula.

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# APPENDIXES

TENNESSEE VALLEY AUTHORITY
Division of Health and Safety

# APPENDIX A

## TABLES

Muscle Shoals, Alabama
September 1968

Table 1

PLANT DESIGN AND OPERATIONAL DATA

| | Paradise | Gallatin | Shawnee | Johnsonville | Colbert | Widows Creek |
|---|---|---|---|---|---|---|
| Number of Units | 2 | 4 | 10 | 4 | 4 | 1 |
| Rated Capacity, per unit (megawatts) | 704 | 314 | 175 | 172.8 | 206 | 575 |
| Stacks, Number | 2 | 2 | 10 | 2 | 4 | 1 |
| Height (meters) | 182.9 | 152.4 | 76.2 | 121.9 | 91.4 | 152.4 |
| Diameter (meters) | 7.9 | 7.6 | 4.3 | 4.3 | 5.0 | 6.3 |
| Spacing (meters) | 61.9 | 77.4 | 25.2 | 49.4 | 30.2 | |
| Temperature of flue gas leaving stack (°C.) | 140.0 | 136.7 | 140.0 | 151.7 | 170.6 | 141.1 |
| Orientation | N 38° E | N 39° E | N 56° W | N 5° W | S 45° E | |

Table 2

PLUME RISE ABOVE STACK TOP WITH DISTANCE FROM PLANT

| Steam Plant | Obs. No. | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | x = 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Paradise | 1 | 0 | 20 | 32 | 46 | 44 | 49 | 62 | 74 | 86 | 89 |
| | 2 | 0 | 31 | 50 | 67 | 71 | 95 | 119 | 143 | 167 | 179 |
| | 3 | 0 | 59 | 93 | 109 | 110 | 147 | 184 | 221 | 256 | - |
| | 4 | 0 | 31 | 44 | 66 | 84 | 96 | 100 | 98 | 104 | 115 |
| | 5 | 2 | 59 | 80 | 112 | 136 | 153 | 165 | 173 | 182 | 188 |
| | 6 | 1 | 97 | 160 | 228 | 269 | 304 | 327 | 340 | 354 | 375 |
| | 7 | 0 | 57 | 104 | 160 | 185 | 191 | 195 | 193 | 183 | 187 |
| | 8 | 25 | 48 | 77 | 126 | 166 | 203 | 230 | 255 | 275 | 295 |
| | 9 | 12 | 92 | 145 | 203 | 217 | 250 | 283 | 313 | 338 | 363 |
| | 10 | 14 | 118 | 168 | 261 | 302 | 307 | 331 | 323 | 330 | 307 |
| | 11 | 3 | 66 | 107 | 169 | 214 | 247 | 273 | 292 | 309 | 329 |
| | 12 | 12 | 80 | 124 | 175 | 214 | 247 | 277 | 307 | 334 | 363 |
| | 13 | 94 | 178 | 240 | 312 | 358 | 394 | 417 | 433 | 447 | 457 |
| | 14 | 4 | 39 | 62 | 98 | 132 | 162 | 184 | 201 | - | - |
| | 15 | 2 | 43 | 66 | 106 | 134 | 163 | 198 | 226 | - | - |
| | 16 | 1 | 29 | 53 | 90 | 121 | 148 | 175 | 207 | 217 | 251 |
| | 17 | 0 | 25 | 39 | 62 | 81 | 92 | 102 | 115 | 119 | 127 |
| | 18 | 1 | 30 | 55 | 91 | 117 | 136 | 156 | 167 | 172 | 183 |
| | 19 | 0 | 22 | 42 | 79 | 117 | 150 | 174 | 194 | 215 | 237 |
| | 20 | 0 | 10 | 21 | 53 | 82 | 106 | 128 | 149 | 170 | 176 |
| | 21 | 0 | 34 | 54 | 78 | 102 | 126 | 148 | 167 | 188 | 242 |
| | 22 | 0 | 33 | 62 | 92 | 115 | 140 | 159 | 182 | 201 | 219 |
| | 23 | 0 | 25 | 44 | 65 | 84 | 112 | 115 | 133 | 154 | 177 |
| | 24 | 0 | 16 | 29 | 50 | 76 | 96 | 111 | 122 | 139 | 145 |
| | 25 | 0 | 13 | 26 | 47 | 62 | 70 | 85 | 93 | 105 | 135 |
| | 26 | 0 | 26 | 43 | 63 | 78 | 93 | 110 | 106 | - | - |
| | 27 | 0 | 25 | 43 | 62 | 67 | 89 | 107 | 103 | 108 | - |
| | 28 | 0 | 34 | 50 | 61 | 64 | 77 | 86 | 94 | - | - |
| | 29 | 0 | 27 | 41 | 54 | 60 | 69 | 88 | 102 | 109 | 98 |
| | 30 | 0 | 44 | 74 | 119 | 166 | 194 | 227 | 260 | 289 | 308 |

Table 2 (continued)

| Steam Plant | Obs. No. | x = 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
|---|---|---|---|---|---|---|---|---|---|---|---|
| | | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
| Paradise (cont'd) | 31 | 0 | 59 | 94 | 117 | 132 | 154 | 152 | 160 | 171 | 178 |
| | 32 | 4 | 60 | 101 | 150 | 181 | 213 | 239 | 258 | - | - |
| | 33 | 15 | 74 | 113 | 163 | 207 | 250 | 279 | 297 | 303 | 328 |
| | 34 | 1 | 49 | 94 | 152 | 205 | 254 | 229 | 307 | 370 | 306 |
| | 35 | 0 | 34 | 55 | 98 | 140 | 174 | 204 | 232 | 257 | 279 |
| | 36 | 1 | 52 | 84 | 138 | 174 | 205 | 227 | 250 | 267 | 283 |
| | 37 | 0 | 40 | 69 | 124 | 173 | 206 | 238 | 268 | 285 | 305 |
| | 38 | 0 | 16 | 30 | 48 | 62 | 77 | 91 | 104 | 114 | 124 |
| | 39 | 0 | 18 | 34 | 55 | 74 | 95 | 112 | 125 | 139 | 150 |
| | 40 | 0 | 14 | 26 | 52 | 84 | 102 | 116 | 134 | 158 | 165 |
| | 41 | 0 | 27 | 40 | 51 | 66 | 86 | 113 | 131 | 143 | 154 |
| | 42 | 0 | 37 | 62 | 88 | 106 | 133 | 154 | 175 | 191 | - |
| | 43 | 0 | 53 | 87 | 121 | 137 | 141 | 165 | 182 | - | - |
| | 44 | 0 | 43 | 81 | 143 | 180 | 204 | 220 | 230 | 238 | 245 |
| | 45 | 2 | 66 | 115 | 191 | 244 | 283 | 308 | 332 | 350 | 364 |
| | 46 | 0 | 46 | 85 | 144 | 198 | 245 | 296 | 343 | 384 | 414 |
| | 47 | 0 | 21 | 36 | 60 | 78 | 93 | 107 | 120 | 135 | 143 |
| | 48 | 0 | 19 | 34 | 66 | 90 | 115 | 136 | 152 | 167 | 185 |
| | 49 | 0 | 27 | 50 | 87 | 116 | 142 | 169 | 193 | 213 | 233 |
| | 50 | 0 | 16 | 34 | 66 | 83 | 100 | 111 | 119 | 124 | 125 |
| Gallatin | 1 | 1,025 | - | - | - | - | - | - | - | - | - |
| | 2 | 488 | - | - | - | - | - | - | - | - | - |
| | 3 | 0 | 20 | 41 | 81 | 121 | 162 | 202 | 239 | 276 | 312 |
| | 4 | 0 | 22 | 43 | 87 | 130 | 173 | 216 | 248 | 276 | 303 |
| | 5 | 777 | - | - | - | - | - | - | - | - | - |
| | 6 | 0 | 13 | 26 | 52 | 78 | 104 | 130 | 144 | 155 | 165 |
| | 7 | 0 | 16 | 32 | 63 | 95 | 127 | 159 | 178 | 192 | 207 |
| | 8 | 0 | 16 | 31 | 62 | 94 | 125 | 156 | 183 | 199 | 215 |
| | 9 | 0 | 17 | 34 | 69 | 103 | 138 | 172 | 189 | 198 | 208 |
| | 10 | 0 | 16 | 31 | 62 | 93 | 124 | 155 | 167 | 173 | 180 |

Table 2 (continued)

| Steam Plant | Obs. No. | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Gallatin (cont'd) | 11 | | 0 | 9 | 119 | 37 | 55 | 74 | 93 | 111 | 130 | - |
| | 12 | | 13 | 64 | 93 | 127 | 160 | 176 | 214 | - | - | - |
| | 13 | | 56 | 124 | 192 | 322 | 382 | 414 | 444 | 417 | 460 | 450 |
| | 14 | | 27 | 72 | 117 | 171 | 224 | 285 | 335 | 386 | 464 | 555 |
| | 15 | | 476 | 451 | 430 | - | - | - | - | - | - | - |
| | 16 | | 21 | 49 | 76 | 132 | 175 | 184 | 194 | 208 | 215 | 226 |
| | 17 | | 32 | 70 | 109 | 185 | 238 | 248 | 259 | 266 | 317 | 300 |
| | 18 | | 14 | 37 | 62 | 109 | 157 | 196 | 220 | 251 | 276 | 314 |
| | 19 | | 19 | 43 | 68 | 118 | 161 | 168 | 181 | 194 | 210 | 220 |
| | 20 | | 16 | 46 | 76 | 135 | 194 | 251 | 286 | 321 | 330 | 354 |
| | 21 | | 25 | 46 | 67 | 109 | 142 | 156 | 163 | 166 | 168 | 171 |
| | 22 | | 66 | 95 | 124 | 182 | 234 | 249 | 251 | 243 | 235 | 228 |
| | 23 | | 73 | 112 | 150 | 228 | 300 | 341 | 347 | 322 | 287 | 270 |
| | 24 | | 5 | 81 | 127 | 183 | 220 | 250 | 274 | 310 | 335 | 359 |
| | 25 | | 0 | 43 | 66 | 90 | 128 | 171 | 192 | 227 | 247 | 259 |
| | 26 | | 0 | 24 | 45 | 63 | 81 | 99 | 98 | 109 | 109 | 137 |
| | 27 | | 0 | 26 | 46 | 72 | 91 | 103 | 109 | 143 | 165 | - |
| | 28 | | 1 | 47 | 63 | 83 | 112 | 135 | 166 | 196 | 220 | 250 |
| | 29 | | 0 | 59 | 74 | 111 | 142 | 171 | 198 | 228 | 251 | 263 |
| | 30 | | 0 | 48 | 59 | 81 | 81 | 101 | 120 | - | - | - |
| | 31 | | 21 | 77 | 104 | 136 | 163 | 173 | - | - | - | - |
| | 32 | | 0 | 23 | 37 | 57 | 68 | 77 | 86 | 90 | 91 | 96 |
| | 33 | | 345 | 440 | 529 | 511 | 466 | - | - | - | - | - |
| | 34 | | 9 | 62 | 131 | 226 | 240 | - | - | - | - | - |
| | 35 | | 0 | 25 | 45 | 69 | 92 | 112 | 128 | 138 | 137 | 129 |
| | 36 | | 0 | 9 | 15 | 21 | 35 | 52 | - | - | - | - |
| | 37 | | 0 | 15 | 25 | 51 | 81 | 99 | 105 | 122 | - | - |
| | 38 | | 0 | 16 | 24 | 38 | 52 | 77 | 128 | - | - | - |

Table 2 (continued)

| Steam Plant | Obs. No. | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Shawnee | 1 | | 14 | 70 | 127 | 234 | 330 | 407 | 457 | 495 | 546 | 526 |
| | 2 | | 27 | 81 | 134 | 203 | 242 | 258 | 266 | 266 | 260 | 240 |
| | 3 | | 0 | 20 | 40 | 87 | 136 | 160 | 186 | 200 | 220 | 236 |
| | 4 | | 0 | 58 | 113 | 195 | 265 | 318 | 365 | 460 | 446 | 493 |
| | 5 | | 0 | 9 | 13 | 15 | 16 | 18 | 22 | - | - | - |
| | 6 | | 0 | 18 | 28 | 39 | 43 | 45 | 48 | - | - | - |
| | 7 | | 0 | 15 | 26 | 44 | 58 | 68 | 88 | - | - | - |
| | 8 | | 0 | 11 | 22 | 35 | 42 | 47 | 53 | 45 | 31 | 24 |
| | 9 | | 0 | 6 | 13 | 20 | 29 | 29 | 26 | 21 | 16 | - |
| | 10 | | 0 | 11 | 20 | 39 | 60 | 80 | 99 | 126 | 120 | - |
| | 11 | | 0 | 16 | 32 | 52 | 67 | 78 | 79 | - | - | - |
| | 12 | | 0 | 13 | 25 | 41 | 50 | 53 | 54 | 57 | 61 | 68 |
| Johnsonville | 1 | | 58 | 118 | 156 | 198 | 212 | 210 | 208 | 201 | - | - |
| | 2 | | 107 | 143 | 179 | 251 | 323 | 363 | 375 | - | - | - |
| | 3 | | 720 | - | - | - | - | - | - | - | - | - |
| | 4 | | 69 | 193 | 294 | 424 | 474 | 480 | 492 | - | - | - |
| | 5 | | 81 | 186 | 268 | 368 | 393 | 375 | 357 | - | - | - |
| | 6 | | 46 | 245 | 366 | 466 | 453 | 418 | 400 | 400 | - | - |
| | 7 | | 58 | 171 | 258 | 357 | 434 | 501 | 556 | 586 | 627 | 661 |
| | 8 | | 7 | 38 | 59 | 77 | 91 | 101 | 105 | 119 | 112 | 97 |
| | 9 | | 22 | 72 | 112 | 166 | 203 | 211 | 206 | 224 | 225 | 293 |
| | 10 | | 324 | 320 | 316 | 453 | 498 | - | - | - | - | - |
| | 11 | | 22 | 62 | 81 | 108 | 126 | 142 | 156 | 167 | 176 | 185 |
| | 12 | | 32 | 100 | 137 | 187 | 221 | 232 | 241 | 244 | 242 | 249 |
| | 13 | | 46 | 116 | 166 | 246 | 320 | 368 | 414 | 405 | 379 | 347 |

Table 2 (continued)

| Steam Plant | Obs. No. | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Colbert | 1 | | 302 | 365 | 389 | 401 | 403 | 388 | - | - | - | - |
| | 2 | | 297 | 405 | 430 | 429 | - | - | - | - | - | - |
| | 3 | | 36 | 87 | 121 | 148 | 162 | 171 | 178 | 192 | 219 | - |
| | 4 | | 10 | 75 | 122 | 176 | 212 | 255 | 280 | 290 | 311 | - |
| | 5 | | 2 | 41 | 81 | 150 | 205 | 241 | 272 | 293 | 315 | 340 |
| | 6 | | 12 | 58 | 95 | 122 | 136 | 144 | 149 | 152 | 143 | 164 |
| | 7 | | 17 | 72 | 118 | 154 | 172 | 182 | 195 | 199 | 219 | 233 |
| | 8 | | 48 | 123 | 190 | 269 | 314 | 333 | 344 | 354 | 362 | 365 |
| | 9 | | 2 | 49 | 89 | 122 | 140 | 148 | 151 | 151 | 149 | 148 |
| | 10 | | 15 | 66 | 146 | 220 | 253 | 268 | 277 | 301 | - | - |
| Widows Creek | 1 | | 0 | 21 | 42 | 61 | 77 | 93 | 103 | 117 | 117 | 136 |
| | 2 | | 0 | 23 | 44 | 63 | 77 | 99 | 103 | 125 | 119 | - |
| | 3 | | 5 | 37 | 57 | 80 | 103 | 130 | 155 | 155 | 149 | - |
| | 4 | | 72 | 190 | 262 | 323 | 356 | 345 | 377 | - | - | - |
| | 5 | | 56 | 120 | 163 | 208 | 243 | 304 | - | - | - | - |
| | 6 | | 130 | 258 | 314 | 331 | 333 | - | - | - | - | - |
| | 7 | | 1 | 55 | 71 | 73 | - | - | - | - | - | - |
| | 8 | | 18 | 63 | 86 | 126 | 129 | 134 | 138 | - | - | - |
| | 9 | | 18 | 81 | 111 | 154 | 190 | 214 | 238 | 301 | - | - |
| | 10 | | 22 | 101 | 136 | 205 | 286 | 316 | 278 | - | - | - |

Table 3

AVERAGE PLUME RISE WITH DISTANCE FROM SOURCE BY STABILITY CLASSES

SINGLE STACK OPERATION

| Steam Plant | Obs. No. | $Q_H$ (cal./sec. x $10^7$) | Stability (°K/100 m.) | Stability Class* | $V_s$ (m./sec.) | $\bar{u}$ (m./sec.) | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Paradise | 1 | 1.70 | 1.73 | 1 | 15.6 | 8.5 | | 0 | 20 | 32 | 46 | 44 | 49 | 62 | 74 | 86 | 89 |
| | 4 | 1.86 | 1.37 | 1 | 16.4 | 8.1 | | 0 | 31 | 44 | 66 | 84 | 96 | 100 | 98 | 104 | 115 |
| | Avg. | 1.78 | 1.55 | | 16.0 | 8.3 | | 0 | 26 | 38 | 56 | 64 | 73 | 81 | 86 | 95 | 102 |
| | 38 | 2.44 | 1.12 | 1 | 19.1 | 16.8 | | 0 | 16 | 30 | 48 | 62 | 77 | 91 | 104 | 114 | 124 |
| Gallatin | 21 | 1.77 | 1.06 | 1 | 15.3 | 4.6 | | 25 | 46 | 67 | 109 | 142 | 156 | 163 | 166 | 168 | 171 |
| Widows Creek | 4 | 1.79 | 1.32 | 1 | 22.9 | 2.5 | | 72 | 190 | 262 | 323 | 356 | 345 | 377 | | | |
| Paradise | 10 | 2.02 | 0.01 | 2 | 17.8 | 1.9 | | 14 | 118 | 168 | 261 | 302 | 307 | 331 | 323 | 330 | 307 |
| | 9 | 2.02 | 0.17 | 2 | 17.8 | 3.3 | | 12 | 92 | 145 | 203 | 217 | 250 | 283 | 313 | 338 | 363 |
| | 13 | 1.87 | 0.30 | 2 | 17.1 | 3.4 | | 94 | 178 | 240 | 312 | 358 | 394 | 417 | 433 | 447 | 457 |
| | 12 | 1.87 | 0.65 | 2 | 17.1 | 3.7 | | 12 | 80 | 124 | 175 | 214 | 247 | 277 | 307 | 334 | 363 |
| | Avg. | 1.93 | 0.28 | | 17.5 | 3.1 | | 33 | 117 | 169 | 238 | 273 | 300 | 327 | 344 | 362 | 373 |
| | 8 | 2.02 | 0.44 | 2 | 17.8 | 4.1 | | 25 | 48 | 77 | 126 | 166 | 203 | 230 | 255 | 275 | 295 |
| | 11 | 1.87 | 0.59 | 2 | 17.1 | 4.5 | | 3 | 66 | 107 | 169 | 214 | 247 | 273 | 292 | 309 | 329 |
| | 7 | 1.86 | 0.01 | 2 | 16.4 | 4.7 | | 0 | 57 | 104 | 160 | 185 | 191 | 195 | 193 | 183 | 187 |
| | 30 | 2.00 | 0.08 | 2 | 16.4 | 5.2 | | 0 | 44 | 74 | 119 | 166 | 194 | 227 | 260 | 289 | 308 |
| | 43 | 2.46 | 0.11 | 2 | 19.2 | 5.2 | | 0 | 53 | 87 | 121 | 137 | 141 | 165 | 182 | | |
| | Avg. | 2.04 | 0.25 | | 17.4 | 4.7 | | 6 | 54 | 90 | 139 | 174 | 195 | 218 | 236 | 264 | 280 |
| | 5 | 1.86 | 0.85 | 2 | 16.4 | 6.0 | | 2 | 59 | 80 | 112 | 136 | 153 | 165 | 173 | 182 | 188 |
| | 22 | 1.84 | 0.28 | 2 | 15.6 | 7.7 | | 0 | 33 | 62 | 92 | 115 | 140 | 159 | 182 | 201 | 219 |
| | Avg. | 1.85 | 0.57 | | 16.0 | 6.9 | | 1 | 46 | 71 | 102 | 126 | 147 | 162 | 178 | 192 | 204 |
| | 39 | 2.44 | 0.37 | 2 | 19.1 | 13.8 | | 0 | 18 | 34 | 55 | 74 | 95 | 112 | 125 | 139 | 150 |
| | 42 | 2.46 | 0.27 | 2 | 19.2 | 8.0 | | 0 | 37 | 62 | 88 | 106 | 133 | 154 | 175 | 191 | |
| | 41 | 2.44 | 0.09 | 2 | 19.1 | 8.4 | | 0 | 27 | 40 | 51 | 66 | 86 | 113 | 131 | 143 | 154 |
| | Avg. | 2.45 | 0.18 | | 19.2 | 8.2 | | 0 | 32 | 51 | 70 | 86 | 110 | 134 | 153 | 167 | 154 |
| | 28 | 2.18 | 0.02 | 2 | 18.0 | 10.0 | | 0 | 34 | 56 | 61 | 64 | 77 | 86 | 94 | | |
| | 40 | 2.44 | 0.02 | 2 | 19.1 | 10.6 | | 0 | 14 | 26 | 52 | 84 | 102 | 116 | 134 | 158 | 165 |
| | 26 | 2.18 | 0.01 | 2 | 18.0 | 10.8 | | 0 | 26 | 43 | 63 | 78 | 93 | 110 | 106 | | |
| | 25 | 1.84 | 0.18 | 2 | 15.6 | 11.4 | | 0 | 13 | 26 | 47 | 62 | 70 | 85 | 93 | 105 | 135 |
| | Avg. | 2.16 | 0.06 | | 17.7 | 10.7 | | 0 | 22 | 36 | 56 | 72 | 86 | 99 | 107 | 132 | 150 |
| Gallatin | 1 | 1.76 | 0.35 | 2 | 15.4 | 1.0 | | 1,025 | | | | | | | | | |
| | 2 | 1.76 | 0.09 | 2 | 15.4 | 1.3 | | 488 | | | | | | | | | |
| | 5 | 1.76 | 0.35 | 2 | 15.4 | 1.3 | | 777 | | | | | | | | | |
| | Avg. | 1.76 | 0.26 | | 15.4 | 1.2 | | 763 | | | | | | | | | |

Table 3 (continued)

| Steam Plant | Obs. No. | $Q_H$ (cal./sec. x $10^7$) | Stability (°K/100 m.) | Stability Class* | $V_s$ (m./sec.) | $\bar{u}$ (m./sec.) | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Gallatin (cont'd) | 15 | 1.70 | 0.30 | 2 | 15.3 | 2.1 | | 476 | 451 | 430 | | | | | | | |
| | 13 | 1.70 | 0.09 | 2 | 15.3 | 2.2 | | 56 | 124 | 192 | 322 | 382 | 414 | 444 | 417 | 460 | 450 |
| | 4 | 1.76 | 0.41 | 2 | 15.4 | 2.5 | | 0 | 22 | 43 | 87 | 130 | 173 | 216 | 248 | 276 | 303 |
| | 23 | 1.77 | 0.36 | 2 | 15.3 | 2.5 | | 73 | 112 | 150 | 228 | 300 | 341 | 347 | 322 | 287 | 270 |
| | 3 | 1.76 | 0.63 | 2 | 15.4 | 2.8 | | 0 | 20 | 41 | 81 | 121 | 161 | 202 | 239 | 276 | 312 |
| | 17 | 1.71 | 0.44 | 2 | 15.6 | 2.9 | | 32 | 70 | 109 | 185 | 238 | 248 | 259 | 266 | 317 | 300 |
| | 28 | 1.52 | 0.06 | 2 | 15.2 | 3.1 | | 1 | 47 | 63 | 83 | 112 | 139 | 166 | 196 | 220 | 250 |
| | 14 | 1.70 | 0.23 | 2 | 15.3 | 2.1 | | 27 | 72 | 117 | 171 | 224 | 285 | 335 | 386 | 464 | 555 |
| | 22 | 1.77 | 0.97 | 2 | 15.3 | 3.2 | | 66 | 95 | 124 | 182 | 234 | 249 | 251 | 243 | 235 | 228 |
| | Avg. | 1.71 | 0.39 | | 15.3 | 2.6 | | 104 | 113 | 141 | 167 | 218 | 251 | 278 | 290 | 317 | 334 |
| | 25 | 1.50 | 0.10 | 2 | 14.8 | 4.6 | | 0 | 43 | 66 | 90 | 128 | 171 | 192 | 227 | 247 | 259 |
| | 7 | 1.74 | 0.22 | 2 | 16.1 | 5.0 | | 0 | 16 | 32 | 63 | 95 | 127 | 159 | 178 | 192 | 207 |
| | 19 | 1.65 | 0.68 | 2 | 15.5 | 5.0 | | 19 | 43 | 68 | 118 | 161 | 168 | 181 | 194 | 210 | 220 |
| | 16 | 1.71 | 0.74 | 2 | 15.6 | 5.1 | | 21 | 49 | 76 | 132 | 175 | 184 | 194 | 208 | 215 | 226 |
| | 24 | 1.50 | 0.61 | 2 | 14.8 | 5.2 | | 5 | 81 | 187 | 183 | 220 | 250 | 274 | 310 | 335 | 359 |
| | 9 | 1.75 | 0.39 | 2 | 16.4 | 5.4 | | 0 | 17 | 34 | 69 | 103 | 138 | 172 | 189 | 198 | 208 |
| | 8 | 1.74 | 0.11 | 2 | 16.1 | 5.8 | | 0 | 16 | 31 | 62 | 94 | 125 | 156 | 183 | 199 | 215 |
| | 6 | 1.74 | 0.72 | 2 | 16.1 | 5.9 | | 0 | 13 | 26 | 52 | 78 | 104 | 130 | 144 | 155 | 165 |
| | Avg. | 1.67 | 0.45 | | 15.7 | 5.3 | | 6 | 35 | 58 | 96 | 132 | 158 | 182 | 204 | 219 | 232 |
| | 10 | 1.73 | 0.30 | 2 | 15.4 | 6.9 | | 0 | 16 | 31 | 62 | 93 | 124 | 155 | 167 | 173 | 180 |
| | 27 | 1.50 | 0.13 | 2 | 14.8 | 10.4 | | 0 | 26 | 46 | 72 | 91 | 103 | 109 | 143 | 165 | |
| Widows Creek | 6 | 1.79 | 0.04 | 2 | 22.9 | 2.2 | | 130 | 258 | 314 | 331 | 333 | | | | | |
| | 10 | 1.57 | 0.09 | 2 | 22.9 | 2.4 | | 22 | 101 | 136 | 205 | 286 | 316 | 278 | | | |
| | 5 | 1.79 | 0.49 | 2 | 22.9 | 3.4 | | 56 | 120 | 163 | 208 | 243 | 304 | | | | |
| | Avg. | 1.72 | 0.21 | | 22.9 | 2.7 | | 69 | 160 | 204 | 248 | 287 | 310 | 278 | | | |
| | 9 | 1.57 | 0.25 | 2 | 22.9 | 4.1 | | 18 | 81 | 111 | 154 | 190 | 214 | 238 | 301 | | |
| | 3 | 1.77 | 0.02 | 2 | 22.9 | 4.8 | | 5 | 37 | 57 | 80 | 103 | 130 | 155 | 155 | 149 | |
| | 8 | 1.57 | 0.22 | 2 | 22.9 | 5.2 | | 18 | 63 | 86 | 126 | 129 | 134 | 138 | | | |
| | Avg. | 1.64 | 0.16 | | 22.9 | 4.7 | | 14 | 60 | 85 | 120 | 141 | 159 | 177 | 228 | 149 | |
| | 1 | 1.77 | 0.19 | 2 | 22.9 | 6.5 | | 0 | 21 | 42 | 61 | 77 | 93 | 103 | 117 | 117 | 136 |
| Paradise | 6 | 1.86 | 0 | 3 | 16.4 | 2.6 | | 1 | 97 | 160 | 228 | 269 | 304 | 327 | 340 | 354 | 375 |
| | 3 | 1.70 | -0.09 | 3 | 15.6 | 4.9 | | 0 | 59 | 93 | 102 | 110 | 147 | 184 | 221 | 256 | |
| | 31 | 2.00 | -0.02 | 3 | 16.4 | 5.7 | | 0 | 59 | 94 | 117 | 132 | 154 | 152 | 160 | 171 | 178 |
| | Avg. | 1.85 | -0.06 | | 16.0 | 5.3 | | 0 | 59 | 94 | 113 | 121 | 151 | 168 | 191 | 214 | 178 |
| | 2 | 1.70 | -0.05 | 3 | 15.6 | 6.8 | | 0 | 31 | 50 | 67 | 71 | 95 | 119 | 143 | 167 | 179 |
| | 24 | 1.84 | -0.13 | 3 | 15.6 | 7.2 | | 0 | 16 | 29 | 50 | 76 | 96 | 111 | 122 | 139 | 145 |
| | 21 | 1.78 | -0.17 | 3 | 15.3 | 7.3 | | 0 | 34 | 54 | 78 | 102 | 126 | 148 | 167 | 188 | 242 |
| | Avg. | 1.77 | -0.12 | | 15.5 | 7.1 | | 0 | 27 | 44 | 65 | 83 | 106 | 126 | 144 | 165 | 189 |
| | 23 | 1.84 | -0.04 | 3 | 15.6 | 10.9 | | 0 | 25 | 44 | 65 | 84 | 112 | 115 | 133 | 154 | 177 |

Table 3 (continued)

| Steam Plant | Obs. No. | $Q_H$ (cal./sec. x $10^7$) | Stability (°K/100 m.) | Stability Class* | $V_s$ (m./sec.) | $\bar{u}$ (m./sec.) | x = | Plume Rise (meters) at Distance Downwind, x (meters) | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | 0 | 76 | 152 | 305 | 457 | 610 | 762 | 914 | 1,067 | 1,219 |
| Gallatin | 12 | 1.70 | -0.03 | 3 | 15.3 | 3.8 | | 13 | 64 | 93 | 127 | 160 | 176 | 214 | | | |
| | 29 | 1.52 | -0.00 | 3 | 15.2 | 4.4 | | 0 | 59 | 74 | 111 | 142 | 171 | 198 | 228 | 251 | 263 |
| | Avg. | 1.61 | -0.02 | | 15.3 | 4.1 | | 7 | 62 | 84 | 119 | 151 | 174 | 206 | 228 | 251 | 263 |
| | 20 | 1.65 | -0.04 | 3 | 15.5 | 5.8 | | 16 | 46 | 76 | 135 | 194 | 251 | 286 | 321 | 330 | 354 |
| | 18 | 1.71 | -0.02 | 3 | 15.6 | 6.1 | | 14 | 37 | 62 | 109 | 157 | 196 | 220 | 251 | 276 | 314 |
| | 11 | 1.73 | -0.16 | 3 | 15.4 | 6.9 | | 0 | 9 | 19 | 37 | 55 | 74 | 93 | 111 | 130 | |
| | Avg. | 1.70 | -0.07 | | 15.5 | 6.3 | | 15 | 31 | 52 | 94 | 135 | 174 | 200 | 228 | 245 | 334 |
| | 26 | 1.50 | 0 | 3 | 14.8 | 9.9 | | 0 | 24 | 45 | 63 | 81 | 99 | 98 | 109 | 109 | 137 |
| Paradise | 29 | 2.18 | -0.02 | 3 | 18.0 | 8.3 | | 0 | 27 | 41 | 54 | 60 | 69 | 88 | 102 | 109 | 98 |
| | 27 | 2.18 | 0 | 3 | 18.0 | 9.5 | | 0 | 25 | 43 | 62 | 67 | 89 | 107 | 103 | 108 | |
| | Avg. | 2.18 | -0.01 | | 18.0 | 8.9 | | 0 | 26 | 42 | 58 | 64 | 79 | 98 | 103 | 109 | 98 |
| Widows Creek | 2 | 1.77 | -0.17 | 3 | 22.9 | 6.0 | | 0 | 23 | 44 | 63 | 77 | 99 | 103 | 125 | 119 | |
| | 7 | 1.59 | -0.18 | 3 | 24.5 | 6.2 | | 1 | 25 | 71 | 73 | | | | | | |
| | Avg. | 1.68 | -0.18 | 3 | 23.7 | 6.1 | | 0 | 24 | 58 | 68 | 77 | 99 | 103 | 125 | 119 | |

*Stability Classification Group

1 $\frac{\Delta\theta}{\Delta z} > 1°$ K/100 m.

2 $0 < \frac{\Delta\theta}{\Delta z} < 1$

3 $\frac{\Delta\theta}{\Delta z} \leq 0$

Table 4

## $\frac{x}{\ell}$ AND $\frac{z}{\ell}$ VALUES - INITIAL PLUME RISE PHASE

### Paradise Steam Plant

| 1* | | 1 | | 2 | | 2 | | 2 | | 2 | | 2 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ |
| 43.1 | 14.7 | 245.8 | 51.6 | 2.1 | 3.3 | 6.8 | 4.8 | 24.6 | 14.8 | 29.3 | 12.3 | 73.3 | 21.2 |
| 86.1 | 21.5 | 491.6 | 96.8 | 4.3 | 4.7 | 13.6 | 8.0 | 49.2 | 22.9 | 58.6 | 19.6 | 146.5 | 34.6 |
| 172.2 | 31.6 | 983.3 | 154.8 | 8.5 | 6.7 | 27.2 | 12.4 | 98.3 | 32.9 | 117.2 | 26.9 | 293.1 | 53.8 |
| 258.3 | 36.2 | 1475.0 | 200.0 | 12.8 | 7.7 | 40.8 | 15.5 | 147.5 | 40.6 | 175.8 | 33.1 | 439.6 | 69.2 |
| 344.4 | 41.2 | 1967.0 | 248.4 | 17.1 | 8.4 | 54.4 | 17.4 | 196.7 | 47.4 | 234.5 | 42.3 | 586.2 | 82.7 |
| 430.5 | 45.8 | 2458.0 | 293.6 | 21.3 | 9.2 | 68.0 | 19.5 | 245.8 | 52.3 | 293.1 | 51.5 | 732.7 | 95.2 |
| 516.6 | 48.6 | 2950.0 | 335.5 | 25.6 | 9.6 | 81.7 | 21.1 | 295.0 | 57.4 | 351.7 | 58.9 | 879.6 | 102.9 |
| 602.7 | 53.7 | 3441.0 | 367.8 | 29.9 | 10.1 | 95.3 | 23.6 | 344.1 | 61.6 | 410.3 | 64.2 | 1026.0 | 127.0 |
| 688.8 | 57.6 | 3933.0 | 400.0 | 34.2 | 10.4 | 108.9 | 24.9 | 393.3 | 65.5 | 468.9 | 59.2 | 1172.0 | 144.2 |

| 2 | | 3 | | 3 | | 3 | | 3 | | 3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ | $\frac{x}{\ell}$ | $\frac{z}{\ell}$ |
| 143.8 | 34.0 | 1.4 | 1.7 | 10.5 | 8.1 | 29.2 | 10.3 | 39.5 | 13.5 | 100.3 | 32.9 |
| 287.6 | 64.2 | 2.7 | 2.9 | 21.0 | 13.0 | 58.4 | 16.9 | 79.0 | 21.8 | 200.6 | 57.9 |
| 575.2 | 103.8 | 5.5 | 4.1 | 42.0 | 15.6 | 116.7 | 24.9 | 157.9 | 30.1 | 401.1 | 85.5 |
| 862.7 | 139.6 | 8.2 | 4.8 | 63.0 | 16.7 | 175.1 | 31.8 | 236.9 | 33.2 | 601.7 | 110.5 |
| 1150.3 | 179.3 | 10.9 | 5.4 | 84.1 | 20.8 | 233.5 | 40.6 | 315.8 | 40.9 | 802.2 | 147.4 |
| 1438.0 | 211.3 | 13.7 | 5.9 | 105.1 | 23.2 | 291.9 | 48.3 | 309.8 | 50.8 | 1003.0 | 151.3 |
| 1726.2 | 235.9 | 16.4 | 6.1 | 126.2 | 26.3 | 350.5 | 55.2 | 474.0 | 53.4 | 1203.9 | 175.0 |
| 2013.1 | 262.3 | 19.1 | 6.3 | 147.1 | 29.5 | 408.7 | 63.2 | 552.7 | 56.5 | 1404.0 | 202.7 |
| 2300.0 | 283.1 | 21.8 | 6.7 | 168.1 | 24.6 | 467.1 | 72.4 | 631.7 | 50.8 | 1604.5 | 232.9 |

*Stability classification data group.

Table 4 (continued)

Gallatin Steam Plant

| 1* | | 2 | | 2 | | 2 | | 2 | | 3 | | 3 | | 3 | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ |
| 8.8 | 5.3 | 1.8 | 2.7 | 12.9 | 5.9 | 30.5 | 6.4 | 94.1 | 32.1 | 5.8 | 4.7 | 24.6 | 10.0 | 87.6 | 27.6 |
| 17.6 | 7.7 | 3.6 | 3.3 | 25.8 | 9.8 | 61.0 | 12.4 | 188.2 | 56.8 | 11.5 | 6.4 | 49.2 | 16.8 | 175.2 | 51.7 |
| 35.1 | 12.6 | 7.2 | 3.9 | 51.7 | 16.3 | 121.9 | 24.8 | 376.4 | 88.9 | 23.1 | 9.0 | 98.3 | 30.3 | 350.3 | 72.4 |
| 52.7 | 16.4 | 10.8 | 5.1 | 77.5 | 22.4 | 182.9 | 37.2 | 564.6 | 112.3 | 34.6 | 11.4 | 147.5 | 43.6 | 525.3 | 93.1 |
| 70.2 | 18.0 | 14.4 | 5.9 | 103.3 | 26.8 | 243.8 | 49.6 | 752.9 | 127.2 | 46.2 | 13.2 | 196.7 | 56.1 | 700.4 | 103.4 |
| 87.8 | 18.8 | 18.0 | 6.6 | 129.2 | 30.8 | 304.8 | 62.0 | 941.1 | 134.6 | 57.7 | 15.6 | 245.8 | 64.5 | 875.5 | 112.6 |
| 105.4 | 19.1 | 21.6 | 6.8 | 155.1 | 34.6 | 365.9 | 66.8 | 1130.0 | 176.6 | 69.3 | 17.3 | 295.1 | 72.9 | 1051.1 | 125.2 |
| 122.9 | 19.4 | 25.2 | 7.5 | 180.8 | 37.1 | 426.7 | 69.2 | 1317.5 | 203.8 | 80.8 | 19.0 | 344.1 | 79.7 | 1226.0 | 125.2 |
| 140.5 | 19.7 | 28.8 | 7.9 | 206.7 | 39.3 | 487.7 | 72.0 | | | 92.4 | 19.9 | | | 1401.0 | 157.4 |

Widows Creek Steam Plant

| 1* | | 2 | | 2 | | 2 | | 3 | |
|---|---|---|---|---|---|---|---|---|---|
| x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ | x/ℓ | z/ℓ |
| 1.2 | 3.1 | 1.7 | 3.5 | 8.2 | 6.4 | 22.2 | 6.1 | 18.0 | 5.7 |
| 2.5 | 4.2 | 3.3 | 4.4 | 16.3 | 9.1 | 44.4 | 12.2 | 35.9 | 13.7 |
| 4.9 | 5.2 | 6.6 | 5.4 | 32.7 | 12.9 | 88.9 | 17.8 | 71.9 | 16.0 |
| 7.3 | 5.7 | 9.9 | 6.2 | 49.0 | 15.1 | 133.3 | 22.4 | 107.8 | 18.2 |
| 9.8 | 5.5 | 13.2 | 6.7 | 65.3 | 17.0 | 177.7 | 27.1 | 143.7 | 23.3 |
| 12.2 | 6.1 | 16.5 | 6.0 | 81.7 | 19.0 | 222.1 | 30.0 | 179.7 | 24.3 |
| | | | | 98.1 | 24.4 | 266.7 | 34.1 | 215.7 | 29.5 |
| | | | | 114.4 | 16.0 | 311.0 | 39.7 | 251.6 | 28.1 |

*Stability classification data group.

Table 5

PRINCIPAL METEOROLOGICAL PARAMETERS AND MAXIMUM PLUME RISE

| Steam Plant | Obs. No. | No. of Stacks | $V_s$ (m./sec.) | $\bar{u}_s$ (m./sec.) | $\bar{u}_3$ (m./sec.) | $\bar{u}_2$ (m./sec.) | $\bar{u}_1$ (m./sec.) | $\bar{u}$ (m./sec.) | $\frac{\Delta\theta}{\Delta z}$ (°K/100 m.) | $\Delta T$ (°K) | $T$ (°K) | Per Stack $Q_H$ (cal./sec. x $10^7$) | Per Stack $Q$ ($m.^3$/sec. x $10^2$) | $\Delta h$ (m.) | $\theta$ (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Paradise | 1 | 1 | 15.6 | 4.8 | 6.4 | 12.4 | 9.4 | 8.5 | 1.73 | 120 | 291 | 1.70 | 5.46 | 89 | |
| | 2 | | | 5.5 | 4.6 | 7.6 | 6.0 | 6.8 | -0.05 | 113 | 298 | 1.70 | 5.59 | 179 | |
| | 3 | | | 4.7 | 4.6 | 5.5 | 5.0 | 4.9 | -0.09 | 111 | 300 | 1.70 | 5.63 | 256 | |
| | 4 | | 16.4 | 7.9 | 8.8 | 9.3 | 9.2 | 8.1 | 1.37 | 121 | 291 | 1.86 | 5.70 | 115 | |
| | 5 | | | 4.8 | 6.0 | 7.3 | 6.7 | 6.0 | 0.85 | 120 | 293 | 1.86 | 5.73 | 188 | |
| | 6 | | | 2.3 | 2.2 | 3.4 | 2.8 | 2.6 | 0.00 | 116 | 297 | 1.86 | 5.81 | 375 | |
| | 7 | | | 5.3 | 5.0 | 3.9 | 4.5 | 4.7 | 0.01 | 114 | 298 | 1.86 | 5.84 | 195 | |
| | 8 | | 17.8 | 5.4 | 4.4 | 2.6 | 3.5 | 4.1 | 0.44 | 119 | 293 | 2.02 | 6.25 | 295 | |
| | 9 | | | 2.7 | 2.9 | 3.5 | 3.2 | 3.3 | 0.17 | 117 | 295 | 2.02 | 6.30 | 363 | |
| | 10 | | | 3.5 | 1.5 | 2.5 | 2.0 | 1.9 | 0.01 | 113 | 299 | 2.02 | 6.38 | 331 | |
| | 11 | | 17.1 | 4.1 | 3.5 | 4.7 | 4.1 | 4.5 | 0.59 | 119 | 293 | 1.87 | 6.02 | 329 | |
| | 12 | | | 2.7 | 3.7 | 4.2 | 3.9 | 3.7 | 0.65 | 120 | 292 | 1.87 | 5.99 | 363 | |
| | 13 | | | 1.6 | 2.7 | 5.2 | 3.9 | 3.4 | 0.30 | 116 | 295 | 1.87 | 6.06 | 457 | |
| | 14 | 2 | 20.2 | 8.6 | 7.7 | 10.5 | 9.1 | 8.8 | 1.42 | 142 | 280 | 2.24 | 6.61 | 201 | 61.9 |
| | 15 | | | 4.3 | 5.5 | 11.9 | 8.7 | 7.7 | 0.55 | 141 | 281 | 2.24 | 6.63 | 226 | 56.9 |
| | 16 | | 17.0 | 8.1 | 7.3 | 6.4 | 6.8 | 7.2 | 0.05 | 126 | 288 | 1.89 | 5.83 | 251 | 30.1 |
| | 17 | | 17.7 | 6.6 | 7.5 | 9.3 | 8.5 | 7.8 | 0.56 | 128 | 287 | 1.97 | 6.04 | 127 | 5.6 |
| | 18 | | | 9.5 | 7.8 | 6.7 | 7.3 | 8.6 | 0.08 | 125 | 291 | 1.97 | 6.11 | 183 | 14.7 |
| | 19 | | | 8.6 | 8.4 | 7.8 | 8.2 | 7.7 | -0.01 | 121 | 294 | 1.97 | 6.19 | 237 | 16.1 |
| | 20 | | | 9.8 | 8.8 | 9.8 | 9.3 | 9.5 | 0.06 | 121 | 295 | 1.97 | 6.20 | 176 | 25.5 |
| | 21 | 1 | 15.3 | 5.1 | 7.6 | 8.7 | 8.1 | 7.3 | -0.17 | 120 | 297 | 1.78 | 5.36 | 242 | |
| | 22 | | 15.6 | 4.8 | 6.0 | 9.2 | 7.5 | 7.7 | 0.28 | 124 | 292 | 1.84 | 5.40 | 219 | |
| | 23 | | | 9.9 | 8.8 | 11.6 | 10.3 | 10.9 | -0.04 | 121 | 294 | 1.84 | 5.44 | 177 | |
| | 24 | | | 6.9 | 7.7 | 7.0 | 7.3 | 7.2 | -0.13 | 118 | 297 | 1.84 | 5.50 | 145 | |
| | 25 | | | 11.3 | 10.9 | 10.0 | 10.5 | 11.4 | 0.18 | 125 | 291 | 1.84 | 5.37 | 135 | |
| | 26 | | 18.0 | 10.3 | 10.4 | 9.8 | 10.2 | 10.8 | 0.01 | 137 | 275 | 2.18 | 5.93 | 110 | |
| | 27 | | | 10.2 | 10.0 | 9.8 | 10.0 | 9.5 | 0.00 | 137 | 275 | 2.18 | 5.94 | 108 | |
| | 28 | | | 9.8 | 7.3 | 10.1 | 8.8 | 10.0 | 0.02 | 136 | 277 | 2.18 | 5.97 | 94 | |
| | 29 | | | 7.4 | 8.0 | 7.3 | 7.6 | 8.3 | -0.02 | 136 | 277 | 2.18 | 5.97 | 109 | |
| | 30 | | 16.4 | 6.9 | 4.5 | 5.1 | 4.8 | 5.2 | 0.08 | 137 | 279 | 2.00 | 5.44 | 308 | |
| | 31 | | | 5.9 | 5.8 | 5.0 | 5.4 | 5.7 | -0.02 | 135 | 281 | 2.00 | 5.48 | 178 | |
| | 32 | 2 | 18.1 | 2.4 | 3.8 | 6.4 | 5.2 | 4.8 | 0.63 | 139 | 281 | 2.22 | 5.96 | 258 | 62.9 |
| | 33 | | | 3.7 | 3.5 | 5.3 | 4.4 | 4.4 | 0.11 | 136 | 284 | 2.22 | 6.02 | 328 | 69.3 |
| | 34 | | | 3.8 | 5.3 | 5.8 | 5.7 | 5.5 | 0.02 | 133 | 287 | 2.22 | 6.09 | 370 | 62.0 |
| | 35 | | 19.0 | 4.5 | 6.3 | 5.7 | 6.0 | 6.8 | 0.65 | 137 | 283 | 2.43 | 6.30 | 279 | 8.7 |
| | 36 | | | 6.9 | 6.0 | 8.0 | 7.0 | 6.6 | 0.46 | 135 | 285 | 2.43 | 6.34 | 283 | 20.2 |
| | 37 | | | 5.5 | 5.6 | 6.2 | 5.8 | 5.8 | 0.03 | 131 | 289 | 2.43 | 6.44 | 305 | 31.6 |
| | 38 | 1 | 19.1 | 10.7 | 13.3 | 21.9 | 17.9 | 16.8 | 1.12 | 140 | 283 | 2.44 | 6.30 | 124 | |
| | 39 | | | 9.6 | 11.3 | 19.1 | 15.3 | 13.8 | 0.37 | 137 | 286 | 2.44 | 6.35 | 150 | |
| | 40 | | | 8.2 | 8.2 | 14.2 | 10.7 | 10.6 | 0.02 | 135 | 288 | 2.44 | 6.40 | 165 | |

Table 5 (continued)

| Steam Plant | Obs. No. | No. of Stacks | $V_s$ (m./sec.) | $\bar{u}_s$ (m./sec.) | $\bar{u}_3$ (m./sec.) | $\bar{u}_2$ (m./sec.) | $\bar{u}_1$ (m./sec.) | $\bar{u}$ (m./sec.) | $\frac{\Delta\theta}{\Delta z}$ (°K/100 m.) | $\Delta T$ (°K) | T (°K) | Per Stack $Q_H$ (cal./sec. x $10^7$) | Per Stack Q (m.$^3$/sec. x $10^2$) | $\Delta h$ (m.) | $\theta$ (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Paradise (cont'd) | 41 | 1 | 19.1 | 8.2 | 7.5 | 8.2 | 7.8 | 8.4 | 0.09 | 132 | 291 | 2.44 | 6.47 | 154 | |
| | 42 | | 19.2 | 5.2 | 5.7 | 9.1 | 7.3 | 8.0 | 0.27 | 145 | 279 | 2.46 | 6.23 | 191 | |
| | 43 | | | 4.6 | 4.6 | 6.8 | 5.8 | 5.2 | 0.11 | 144 | 280 | 2.46 | 6.25 | 182 | |
| | 44 | 2 | 19.5 | 3.6 | 5.2 | 9.0 | 7.2 | 5.9 | 1.54 | 142 | 275 | 2.33 | 6.35 | 245 | 42.1 |
| | 45 | | | 3.7 | 5.0 | 6.4 | 5.7 | 4.2 | 0.53 | 138 | 279 | 2.33 | 6.44 | 364 | 38.0 |
| | 46 | | | 4.6 | 3.9 | 4.5 | 4.2 | 3.7 | 0.03 | 131 | 286 | 2.33 | 6.59 | 414 | 26.2 |
| | 47 | | 18.4 | 7.5 | 9.7 | 12.2 | 10.9 | 10.3 | 1.25 | 138 | 281 | 2.22 | 6.09 | 143 | 10.3 |
| | 48 | | | 5.3 | 5.9 | 10.5 | 8.3 | 8.6 | 0.51 | 135 | 284 | 2.22 | 6.14 | 185 | 11.8 |
| | 49 | | | 9.4 | 7.5 | 9.5 | 8.5 | 8.6 | 0.27 | 133 | 286 | 2.22 | 6.20 | 233 | 12.3 |
| | 50 | | | 7.7 | 8.5 | 11.0 | 9.7 | 8.5 | 0.03 | 130 | 289 | 2.22 | 6.26 | 125 | 8.2 |
| Gallatin | 1 | 1 | 15.4 | 1.0 | 1.8 | 1.5 | 1.7 | 1.0 | 0.35 | 112 | 297 | 1.76 | 5.08 | 1,025 | |
| | 2 | | | 1.0 | 1.5 | 1.9 | 1.7 | 1.3 | 0.09 | 109 | 300 | 1.76 | 5.13 | 488 | |
| | 3 | | | 3.7 | 6.1 | 1.8 | 4.0 | 2.8 | 0.63 | 111 | 299 | 1.76 | 5.11 | 312 | |
| | 4 | | | 2.9 | 2.6 | 2.2 | 2.4 | 2.5 | 0.41 | 114 | 296 | 1.76 | 5.07 | 303 | |
| | 5 | | | 1.4 | 0.8 | 2.7 | 1.8 | 1.3 | 0.35 | 113 | 297 | 1.76 | 5.10 | 777 | |
| | 6 | | 16.1 | 3.8 | 4.9 | 8.2 | 6.5 | 5.9 | 0.72 | 116 | 294 | 1.74 | 5.26 | 165 | |
| | 7 | | | 4.8 | 3.2 | 6.6 | 4.9 | 5.0 | 0.22 | 114 | 296 | 1.74 | 5.29 | 207 | |
| | 8 | | | 5.2 | 5.8 | 4.8 | 5.3 | 5.8 | 0.11 | 111 | 299 | 1.74 | 5.34 | 215 | |
| | 9 | | 16.4 | 2.5 | 5.2 | 8.6 | 6.8 | 5.4 | 0.39 | 113 | 297 | 1.75 | 5.41 | 208 | |
| | 10 | | 15.4 | 5.8 | 6.8 | 9.4 | 8.2 | 6.9 | 0.30 | 112 | 298 | 1.73 | 5.11 | 180 | |
| | 11 | | | 6.5 | 6.4 | 7.4 | 7.0 | 6.9 | -0.16 | 109 | 301 | 1.73 | 5.16 | 130 | |
| | 12 | | 15.3 | 3.8 | 2.9 | 4.1 | 3.5 | 3.8 | -0.03 | 110 | 300 | 1.70 | 5.09 | 214 | |
| | 13 | | | 2.4 | 1.8 | 2.1 | 1.9 | 2.2 | 0.09 | 109 | 301 | 1.70 | 5.11 | 460 | |
| | 14 | | | 2.6 | 2.2 | 1.7 | 1.8 | 2.1 | 0.23 | 110 | 300 | 1.70 | 5.09 | 555 | |
| | 15 | | | 2.8 | - | 1.4 | - | 2.1 | 0.30 | 110 | 300 | 1.70 | 5.10 | 476 | |
| | 16 | | 15.6 | 2.8 | 4.6 | 6.5 | 5.5 | 5.1 | 0.74 | 114 | 296 | 1.71 | 5.15 | 226 | |
| | 17 | | | 1.8 | 3.8 | 3.7 | 3.7 | 2.9 | 0.44 | 112 | 298 | 1.71 | 5.18 | 317 | |
| | 18 | | | 5.3 | 4.6 | 8.7 | 6.7 | 6.1 | -0.02 | 107 | 303 | 1.71 | 5.26 | 314 | |
| | 19 | | 15.5 | 3.3 | 3.6 | 8.6 | 6.2 | 5.0 | 0.68 | 113 | 297 | 1.65 | 5.13 | 220 | |
| | 20 | | | 4.6 | 5.2 | 6.1 | 5.7 | 5.8 | -0.04 | 106 | 304 | 1.65 | 5.25 | 354 | |
| | 21 | | 15.3 | 1.7 | 4.8 | 4.3 | 4.6 | 4.6 | 1.06 | 115 | 295 | 1.77 | 5.03 | 171 | |
| | 22 | | | 1.6 | 4.2 | 3.0 | 3.6 | 3.2 | 0.97 | 113 | 297 | 1.77 | 5.06 | 251 | |
| | 23 | | | 2.7 | 2.6 | 1.9 | 2.3 | 2.5 | 0.36 | 111 | 299 | 1.77 | 5.09 | 347 | |
| | 24 | | 14.8 | 2.8 | 4.0 | 5.3 | 4.7 | 5.2 | 0.61 | 124 | 282 | 1.50 | 4.67 | 359 | |
| | 25 | | | 4.1 | 6.0 | 3.6 | 4.8 | 4.6 | 0.10 | 121 | 286 | 1.50 | 4.73 | 259 | |
| | 26 | | | 8.2 | 7.9 | 11.3 | 9.8 | 9.9 | 0.00 | 117 | 289 | 1.50 | 4.78 | 137 | |
| | 27 | | | 6.7 | 11.6 | 11.7 | 11.7 | 10.4 | 0.13 | 117 | 290 | 1.50 | 4.79 | 165 | |
| | 28 | | 15.2 | 2.7 | 3.3 | 5.1 | 4.3 | 3.1 | 0.06 | 133 | 273 | 1.52 | 4.66 | 250 | |
| | 29 | | | 4.8 | 4.2 | 5.7 | 4.9 | 4.4 | 0.00 | 131 | 275 | 1.52 | 4.69 | 263 | |
| | 30 | | | 3.3 | 3.6 | 4.0 | 3.7 | 3.7 | -0.15 | 125 | 281 | 1.52 | 4.79 | 120 | |

Table 5 (continued)

| Steam Plant | Obs. No. | No. of Stacks | $V_s$ (m./sec.) | $\bar{u}_4$ (m./sec.) | $\bar{u}_3$ (m./sec.) | $\bar{u}_2$ (m./sec.) | $\bar{u}_1$ (m./sec.) | $\bar{u}$ (m./sec.) | $\frac{\Delta\theta}{\Delta z}$ (°K/100 m.) | $\Delta T$ (°K) | T (°K) | Per Stack $Q_H$ (cal./sec. x $10^7$) | Per Stack Q ($m.^3$/sec. x $10^2$) | $\Delta h$ (m.) | $\theta$ (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Gallatin (cont'd) | 31 | 1 | 15.2 | 1.3 | 1.5 | 2.1 | 1.8 | 1.7 | -0.08 | 125 | 281 | 1.52 | 4.80 | 173 | |
| | 32 | 2 | 7.9 | 6.9 | 6.6 | 7.7 | 7.1 | 7.4 | 0.01 | 133 | 285 | 0.870 | 2.46 | 96 | 82.3 |
| | 33 | | 7.7 | 1.0 | 1.3 | 1.1 | 1.2 | 1.2 | 0.70 | 136 | 277 | 0.834 | 2.37 | 529 | 69.8 |
| | 34 | | | 1.6 | 1.6 | 1.6 | 1.6 | 1.5 | 0.23 | 132 | 281 | 0.834 | 2.40 | 240 | 3.9 |
| | 35 | | | 4.6 | 4.7 | 5.7 | 5.1 | 5.1 | -0.05 | 128 | 286 | 0.834 | 2.44 | 138 | 41.0 |
| | 36 | | | 8.9 | 9.9 | 13.1 | 11.7 | 10.8 | 1.51 | 135 | 281 | 0.861 | 2.38 | 52 | 15.4 |
| | 37 | | | 9.5 | 9.2 | 12.7 | 10.8 | 10.5 | 0.93 | 133 | 283 | 0.861 | 2.40 | 122 | 17.5 |
| | 38 | | | 10.0 | 9.5 | 13.3 | 11.4 | 11.8 | 0.11 | 128 | 288 | 0.861 | 2.44 | 128 | 12.6 |
| Shawnee | 1 | 9 | 14.2 | 4.6 | 2.8 | 2.5 | 2.7 | 3.1 | 0.04 | 129 | 290 | 0.557 | 1.40 | 546 | 54.6 |
| | 2 | | 13.8 | 1.6 | 2.4 | 4.7 | 3.5 | 2.5 | 0.27 | 130 | 289 | 0.531 | 1.36 | 266 | 34.2 |
| | 3 | | | 3.5 | 3.4 | 3.5 | 3.4 | 3.8 | 0.07 | 129 | 291 | 0.531 | 1.37 | 236 | 38.0 |
| | 4 | | | 2.3 | 3.0 | 3.8 | 3.5 | 2.4 | -0.08 | 124 | 296 | 0.531 | 1.39 | 493 | 55.8 |
| | 5 | 8 | 14.4 | 5.8 | 0.7 | 6.8 | 3.7 | 6.3 | 3.70 | 134 | 289 | 0.553 | 1.41 | 22 | 79.5 |
| | 6 | | | 4.3 | - | 7.4 | - | 5.9 | 1.64 | 132 | 291 | 0.553 | 1.42 | 48 | 89.7 |
| | 7 | | | 4.5 | - | 9.0 | - | 7.0 | 0.17 | 130 | 294 | 0.553 | 1.43 | 88 | 80.5 |
| | 8 | | | 9.0 | - | 8.1 | - | 8.5 | -0.03 | 126 | 298 | 0.553 | 1.45 | 53 | 75.3 |
| | 9 | | | 8.0 | - | 8.8 | - | 8.7 | -0.49 | 124 | 299 | 0.553 | 1.46 | 29 | 79.2 |
| | 10 | | 14.0 | 5.4 | 3.5 | 7.1 | 5.3 | 6.3 | 0.09 | 129 | 296 | 0.528 | 1.40 | 126 | 68.2 |
| | 11 | | | 6.4 | - | 5.6 | - | 6.4 | -0.35 | 122 | 302 | 0.528 | 1.43 | 79 | 88.0 |
| | 12 | | 14.4 | 5.4 | - | 10.1 | - | 8.8 | 0.38 | 130 | 294 | 0.558 | 1.43 | 68 | 52.2 |
| Johnsonville | 1 | 2 | 28.4 | 1.0 | 3.5 | 2.8 | 3.2 | 2.7 | 1.59 | 131 | 293 | 1.17 | 2.80 | 212 | 5.5 |
| | 2 | | | 2.2 | 2.3 | 1.6 | 2.0 | 2.3 | 0.34 | 126 | 298 | 1.17 | 2.80 | 375 | 16.0 |
| | 3 | | | 1.0 | - | 0.7 | - | 1.0 | 0.00 | 123 | 301 | 1.17 | 2.88 | 720 | 13.0 |
| | 4 | | 29.2 | 1.0 | 1.2 | 1.0 | 1.1 | 1.2 | 1.33 | 137 | 289 | 1.25 | 2.83 | 492 | 19.5 |
| | 5 | | | 1.5 | 1.2 | 1.4 | 1.3 | 1.3 | 1.42 | 133 | 293 | 1.25 | 2.87 | 393 | 25.3 |
| | 6 | | | 1.0 | 1.2 | 0.9 | 1.1 | 1.1 | 0.53 | 128 | 297 | 1.25 | 2.92 | 466 | 15.4 |
| | 7 | | | 1.9 | 1.7 | 2.1 | 1.8 | 2.2 | 0.07 | 124 | 301 | 1.25 | 2.95 | 661 | 13.9 |
| | 8 | | 28.9 | 4.1 | 6.6 | 9.9 | 8.3 | 6.8 | 1.98 | 135 | 290 | 1.22 | 2.82 | 119 | 21.5 |
| | 9 | 2 | 28.9 | 5.2 | 5.5 | 5.1 | 5.3 | 6.1 | 0.62 | 129 | 295 | 1.22 | 2.87 | 293 | 20.3 |
| | 10 | | 26.8 | 1.8 | 2.3 | 1.5 | 1.8 | 1.9 | 0.07 | 131 | 294 | 1.10 | 2.65 | 498 | 30.0 |
| | 11 | | 23.0 | 2.5 | 5.7 | 5.5 | 5.5 | 5.1 | 1.57 | 138 | 288 | 0.98 | 2.23 | 185 | 87.1 |
| | 12 | | | 2.9 | 2.7 | 7.3 | 5.0 | 5.2 | 0.48 | 135 | 291 | 0.98 | 2.25 | 249 | 86.1 |
| | 13 | | | 1.8 | 2.4 | 3.7 | 3.0 | 1.9 | 0.02 | 133 | 293 | 0.98 | 2.27 | 414 | 81.8 |
| Colbert | 1 | 3 | 13.9 | 1.0 | 1.5 | 3.7 | 2.5 | 1.4 | 1.43 | 141 | 273 | 0.844 | 1.82 | 403 | 8.6 |
| | 2 | | | 1.3 | 1.4 | 4.3 | 2.9 | 1.9 | 0.76 | 137 | 278 | 0.844 | 1.85 | 430 | 10.4 |
| | 3 | | | 1.3 | 4.3 | 7.0 | 5.7 | 4.8 | 1.73 | 131 | 284 | 0.703 | 1.88 | 219 | 31.6 |
| | 4 | | | 3.0 | 4.8 | 6.0 | 5.5 | 3.8 | 0.13 | 125 | 290 | 0.703 | 1.92 | 311 | 19.7 |
| | 5 | | | 3.5 | 3.9 | 6.3 | 5.1 | 4.8 | -0.04 | 122 | 293 | 0.703 | 1.94 | 340 | 17.1 |
| | 6 | | 11.6 | 1.6 | 4.6 | 10.1 | 7.8 | 5.3 | 2.99 | 131 | 284 | 0.612 | 1.57 | 164 | 35.4 |
| | 7 | | | 2.0 | 5.1 | 7.1 | 6.1 | 4.2 | 1.86 | 127 | 287 | 0.612 | 1.59 | 233 | 34.7 |
| | 8 | | | 2.7 | 4.2 | 4.3 | 4.3 | 3.2 | 0.19 | 121 | 293 | 0.612 | 1.62 | 365 | 34.7 |
| | 9 | | 12.4 | 2.6 | 4.0 | 5.9 | 5.0 | 4.0 | 2.12 | 131 | 284 | 0.674 | 1.69 | 151 | 79.3 |
| | 10 | 4 | 10.9 | 3.0 | 4.3 | 6.9 | 5.5 | 4.5 | 1.01 | 119 | 295 | 0.539 | 1.54 | 301 | 22.8 |

Table 5 (continued)

| Steam Plant | Obs. No. | No. of Stacks | $V_s$ (m./sec.) | $\bar{u}_4$ (m./sec.) | $\bar{u}_3$ (m./sec.) | $\bar{u}_2$ (m./sec.) | $\bar{u}_1$ (m./sec.) | $\bar{u}$ (m./sec.) | $\frac{\Delta\theta}{\Delta z}$ (°K/100 m.) | $\Delta T$ (°K) | T (°K) | Per Stack $Q_H$ (cal./sec. x $10^7$) | Per Stack Q ($m.^3$/sec. x $10^2$) | $\Delta h$ (m.) | $\theta$ (deg.) |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Widows Creek | 1 | 1 | 22.9 | 4.7 | 5.1 | 5.7 | 5.4 | 6.5 | 0.19 | 119 | 283 | 1.77 | 5.08 | 136 | |
| | 2 | | | 6.6 | 6.4 | 5.3 | 5.8 | 6.0 | -0.17 | 116 | 286 | 1.77 | 5.14 | 125 | |
| | 3 | | | 6.0 | 6.8 | 4.1 | 5.5 | 4.8 | 0.02 | 115 | 287 | 1.77 | 5.16 | 155 | |
| | 4 | | | 1.5 | 3.3 | 4.3 | 3.8 | 2.5 | 1.32 | 121 | 279 | 1.79 | 5.04 | 377 | |
| | 5 | | | 1.9 | 3.5 | 4.1 | 3.8 | 3.4 | 0.49 | 117 | 283 | 1.79 | 5.12 | 304 | |
| | 6 | | | 3.5 | 1.6 | 2.2 | 1.8 | 2.2 | 0.04 | 110 | 290 | 1.79 | 5.24 | 333 | |
| | 7 | | 24.5 | 5.9 | 6.0 | 6.2 | 6.1 | 6.2 | -0.18 | 118 | 280 | 1.59 | 5.44 | 73 | |
| | 8 | | 22.9 | 5.7 | 6.1 | 4.8 | 5.5 | 5.2 | 0.22 | 125 | 275 | 1.57 | 4.97 | 138 | |
| | 9 | | | 3.3 | 3.2 | 5.7 | 4.4 | 4.1 | 0.25 | 122 | 278 | 1.57 | 5.03 | 301 | |
| | 10 | | | 2.0 | 2.9 | 2.7 | 2.8 | 2.4 | 0.09 | 118 | 281 | 1.57 | 5.09 | 316 | |

Table 6

OBSERVED AND CALCULATED PLUME RISE - SINGLE STACK OPERATION

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | Observed Plume Rise (meters) | Calculated Plume Rise (meters) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Holland | Lucas, Moore, & Spurr | Davidson-Bryant | CONCAWE | Bosanquet | Csanady |
| Paradise | 4 | 1 | 8.1 | 115 | 116 | 147 | 27 | 157 | 142 | 310 |
| | 1 | 1 | 8.5 | 89 | 102 | 132 | 24 | 145 | 121 | 245 |
| | 38 | 1 | 16.8 | 124 | 72 | 115 | 13 | 104 | 47 | 59 |
| | 10 | 2 | 1.9 | 331 | 536 | 1,058 | 231 | 486 | 6,000 | 23,382 |
| | 9 | 2 | 3.3 | 363 | 309 | 395 | 107 | 321 | 1,061 | 4,768 |
| | 13 | 2 | 3.4 | 457 | 280 | 332 | 97 | 302 | 831 | 4,471 |
| | 12 | 2 | 3.7 | 363 | 257 | 262 | 87 | 284 | 589 | 3,656 |
| | 8 | 2 | 4.1 | 295 | 249 | 280 | 80 | 273 | 580 | 2,581 |
| | 11 | 2 | 4.5 | 329 | 211 | 243 | 66 | 245 | 456 | 1,998 |
| | 7 | 2 | 4.7 | 195 | 200 | 659 | 58 | 236 | 898 | 1,401 |
| | 30 | 2 | 5.2 | 308 | 191 | 379 | 52 | 227 | 602 | 1,661 |
| | 43 | 2 | 5.2 | 182 | 233 | 369 | 66 | 252 | 643 | 2,241 |
| | 5 | 2 | 6.0 | 188 | 156 | 192 | 42 | 197 | 257 | 734 |
| | 22 | 2 | 7.7 | 219 | 120 | 223 | 28 | 162 | 198 | 348 |
| | 42 | 2 | 8.0 | 191 | 151 | 238 | 36 | 183 | 237 | 624 |
| | 41 | 2 | 8.4 | 154 | 143 | 305 | 33 | 175 | 234 | 423 |
| | 28 | 2 | 10.0 | 94 | 109 | 395 | 24 | 145 | 188 | 284 |
| | 40 | 2 | 10.6 | 165 | 113 | 395 | 24 | 147 | 170 | 218 |
| | 26 | 2 | 10.8 | 110 | 100 | 452 | 22 | 137 | 170 | 230 |
| | 25 | 2 | 11.4 | 135 | 81 | 205 | 16 | 121 | 95 | 109 |
| | 39 | 2 | 13.8 | 150 | 87 | 167 | 16 | 121 | 75 | 102 |
| | 6 | 3 | 2.6 | 375 | 361 | 584 | 133 | 369 | 2,256 | 8,434 |
| | 3 | 3 | 4.9 | 256 | 177 | 303 | 51 | 219 | 111 | 1,081 |
| | 31 | 3 | 5.7 | 178 | 174 | 271 | 46 | 212 | 381 | 1,233 |
| | 2 | 3 | 6.8 | 179 | 127 | 218 | 32 | 171 | 194 | 451 |
| | 24 | 3 | 7.2 | 145 | 128 | 210 | 30 | 171 | 273 | 391 |

Table 6 (continued)

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | Observed Plume Rise (meters) | Calculated Plume Rise (meters) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Holland | Lucas, Moore, & Spurr | Davidson-Bryant | CONCAWE | Bosanquet | Csanady |
| Paradise (cont'd) | 21 | 3 | 7.3 | 242 | 122 | 206 | 29 | 166 | 167 | 393 |
| | 29 | 3 | 8.3 | 109 | 131 | 190 | 31 | 167 | 144 | 497 |
| | 27 | 3 | 9.5 | 108 | 114 | 166 | 26 | 151 | 103 | 338 |
| | 23 | 3 | 10.9 | 177 | 84 | 139 | 17 | 125 | 18 | 118 |
| Gallatin | 21 | 1 | 4.6 | 171 | 192 | 205 | 52 | 234 | 331 | 1,207 |
| | 1 | 2 | 1.0 | 1,025 | 880 | 579 | 445 | 734 | 1,820 | 112,393 |
| | 2 | 2 | 1.3 | 488 | 677 | 714 | 307 | 603 | 3,627 | 47,849 |
| | 5 | 2 | 1.3 | 777 | 677 | 508 | 309 | 603 | 1,735 | 51,157 |
| | 14 | 2 | 2.1 | 555 | 407 | 440 | 155 | 414 | 1,503 | 10,827 |
| | 15 | 2 | 2.1 | 476 | 407 | 412 | 155 | 414 | 1,339 | 10,827 |
| | 13 | 2 | 2.2 | 460 | 388 | 544 | 145 | 399 | 2,033 | 9,310 |
| | 4 | 2 | 2.5 | 303 | 352 | 352 | 124 | 369 | 1,007 | 7,358 |
| | 23 | 2 | 2.5 | 347 | 353 | 364 | 122 | 370 | 1,037 | 6,977 |
| | 3 | 2 | 2.8 | 312 | 314 | 299 | 105 | 339 | 730 | 4,902 |
| | 17 | 2 | 2.9 | 317 | 297 | 319 | 102 | 326 | 814 | 4,393 |
| | 28 | 2 | 3.1 | 250 | 252 | 493 | 93 | 292 | 1,573 | 6,509 |
| | 22 | 2 | 3.2 | 251 | 276 | 251 | 87 | 308 | 540 | 3,473 |
| | 25 | 2 | 4.6 | 259 | 167 | 355 | 51 | 216 | 598 | 1,319 |
| | 7 | 2 | 5.0 | 207 | 176 | 290 | 50 | 218 | 430 | 1,007 |
| | 19 | 2 | 5.0 | 220 | 167 | 216 | 47 | 213 | 324 | 905 |
| | 16 | 2 | 5.1 | 226 | 169 | 211 | 46 | 213 | 311 | 845 |
| | 24 | 2 | 5.2 | 359 | 148 | 212 | 43 | 197 | 327 | 977 |
| | 9 | 2 | 5.4 | 208 | 164 | 242 | 46 | 207 | 333 | 826 |
| | 8 | 2 | 5.8 | 215 | 152 | 320 | 40 | 195 | 360 | 605 |
| | 6 | 2 | 5.9 | 165 | 149 | 199 | 40 | 193 | 253 | 632 |
| | 10 | 2 | 6.9 | 180 | 126 | 228 | 30 | 171 | 212 | 368 |
| | 27 | 2 | 10.4 | 165 | 74 | 221 | 16 | 117 | 103 | 105 |

Table 6 (continued)

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | Observed Plume Rise (meters) | Calculated Plume Rise (meters) | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | Holland | Lucas, Moore, & Spurr | Davidson-Bryant | CONCAWE | Bosanquet | Csanady |
| Gallatin (cont'd) | 12 | 3 | 3.8 | 214 | 225 | 391 | 68 | 265 | 600 | 1,827 |
| | 29 | 3 | 4.4 | 263 | 178 | 328 | 57 | 225 | 658 | 2,039 |
| | 20 | 3 | 5.8 | 354 | 144 | 254 | 38 | 190 | 252 | 500 |
| | 18 | 3 | 6.1 | 314 | 141 | 244 | 36 | 186 | 225 | 424 |
| | 11 | 3 | 6.9 | 130 | 126 | 216 | 30 | 171 | 156 | 349 |
| | 26 | 3 | 9.9 | 137 | 78 | 145 | 17 | 121 | 69 | 125 |
| Widows Creek | 4 | 1 | 2.5 | 377 | 373 | 264 | 182 | 372 | 565 | 11,471 |
| | 6 | 2 | 2.2 | 333 | 424 | 675 | 213 | 410 | 2,492 | 14,186 |
| | 10 | 2 | 2.4 | 316 | 352 | 510 | 192 | 360 | 1,772 | 13,734 |
| | 5 | 2 | 3.4 | 304 | 274 | 290 | 118 | 296 | 614 | 4,304 |
| | 9 | 2 | 4.1 | 301 | 206 | 303 | 91 | 241 | 595 | 2,864 |
| | 3 | 2 | 4.8 | 155 | 196 | 542 | 78 | 227 | 706 | 1,495 |
| | 8 | 2 | 5.2 | 138 | 162 | 277 | 66 | 201 | 418 | 1,458 |
| | 1 | 2 | 6.5 | 136 | 142 | 265 | 48 | 181 | 274 | 638 |
| | 2 | 3 | 6.0 | 125 | 154 | 250 | 53 | 192 | 217 | 778 |

Table 7

OBSERVED AND CALCULATED PLUME RISE - SINGLE STACK OPERATION

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | Observed Plume Rise (meters) | Calculated Plume Rise (meters) Optimized Formulas | | |
|---|---|---|---|---|---|---|---|
| | | | | | CONCAWE | Lucas, Moore, & Spurr | Csanady |
| Paradise | 4 | 1 | 8.1 | 115 | 164 | 127 | 141 |
| | 1 | 1 | 8.5 | 89 | 152 | 115 | 128 |
| | 38 | 1 | 16.8 | 124 | 111 | 94 | 88 |
| | 10 | 2 | 1.9 | 331 | 465 | 860 | 523 |
| | 9 | 2 | 3.3 | 363 | 317 | 339 | 333 |
| | 13 | 2 | 3.4 | 457 | 300 | 289 | 317 |
| | 12 | 2 | 3.7 | 363 | 283 | 232 | 289 |
| | 8 | 2 | 4.1 | 295 | 273 | 243 | 274 |
| | 11 | 2 | 4.5 | 329 | 247 | 213 | 248 |
| | 7 | 2 | 4.7 | 195 | 239 | 509 | 246 |
| | 30 | 2 | 5.2 | 308 | 230 | 309 | 241 |
| | 43 | 2 | 5.2 | 182 | 252 | 302 | 254 |
| | 5 | 2 | 6.0 | 188 | 202 | 167 | 189 |
| | 22 | 2 | 7.7 | 219 | 169 | 185 | 163 |
| | 42 | 2 | 8.0 | 191 | 187 | 195 | 177 |
| | 41 | 2 | 8.4 | 154 | 180 | 241 | 167 |
| | 28 | 2 | 10.0 | 94 | 152 | 296 | 146 |
| | 40 | 2 | 10.6 | 165 | 153 | 294 | 140 |
| | 26 | 2 | 10.8 | 110 | 144 | 331 | 138 |
| | 25 | 2 | 11.4 | 135 | 129 | 164 | 120 |
| | 39 | 2 | 13.8 | 150 | 128 | 133 | 110 |
| | 6 | 3 | 2.6 | 375 | 360 | 470 | 400 |
| | 3 | 3 | 4.9 | 256 | 223 | 245 | 235 |
| | 31 | 3 | 5.7 | 178 | 216 | 217 | 225 |
| | 2 | 3 | 6.8 | 179 | 178 | 176 | 181 |
| | 24 | 3 | 7.2 | 145 | 177 | 169 | 176 |
| | 21 | 3 | 7.3 | 242 | 173 | 166 | 175 |
| | 29 | 3 | 8.3 | 109 | 173 | 152 | 171 |
| | 27 | 3 | 9.5 | 108 | 157 | 133 | 154 |
| | 23 | 3 | 10.9 | 177 | 133 | 112 | 126 |
| Gallatin | 21 | 1 | 4.6 | 171 | 237 | 183 | 218 |
| | 1 | 2 | 1.0 | 1025 | 682 | 547 | 800 |
| | 2 | 2 | 1.3 | 488 | 569 | 637 | 657 |

Table 7 (Continued)

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | Observed Plume Rise (meters) | Calculated Plume Rise (meters) Optimized Formulas | | |
|---|---|---|---|---|---|---|---|
| | | | | | CONCAWE | Lucas, Moore, & Spurr | Csanady |
| Gallatin (cont'd) | 5 | 2 | 1.3 | 777 | 569 | 472 | 649 |
| | 14 | 2 | 2.1 | 555 | 402 | 393 | 440 |
| | 15 | 2 | 2.1 | 476 | 402 | 371 | 437 |
| | 13 | 2 | 2.2 | 460 | 389 | 471 | 428 |
| | 4 | 2 | 2.5 | 303 | 361 | 316 | 381 |
| | 23 | 2 | 2.5 | 347 | 362 | 326 | 378 |
| | 3 | 2 | 2.8 | 312 | 334 | 270 | 336 |
| | 17 | 2 | 2.9 | 317 | 322 | 285 | 336 |
| | 28 | 2 | 3.1 | 250 | 292 | 414 | 352 |
| | 22 | 2 | 3.2 | 251 | 305 | 228 | 293 |
| | 25 | 2 | 4.6 | 259 | 220 | 296 | 243 |
| | 7 | 2 | 5.0 | 207 | 222 | 245 | 224 |
| | 19 | 2 | 5.0 | 220 | 217 | 189 | 211 |
| | 16 | 2 | 5.1 | 226 | 218 | 185 | 208 |
| | 24 | 2 | 5.2 | 359 | 202 | 186 | 211 |
| | 9 | 2 | 5.4 | 208 | 211 | 207 | 207 |
| | 8 | 2 | 5.8 | 215 | 200 | 263 | 199 |
| | 6 | 2 | 5.9 | 165 | 198 | 172 | 188 |
| | 10 | 2 | 6.9 | 180 | 177 | 191 | 168 |
| | 27 | 2 | 10.4 | 165 | 125 | 177 | 124 |
| | 12 | 3 | 3.8 | 214 | 267 | 316 | 279 |
| | 29 | 3 | 4.4 | 263 | 229 | 267 | 265 |
| | 20 | 3 | 5.8 | 354 | 196 | 206 | 196 |
| | 18 | 3 | 6.1 | 314 | 192 | 197 | 189 |
| | 11 | 3 | 6.9 | 130 | 177 | 174 | 174 |
| | 26 | 3 | 9.9 | 137 | 130 | 118 | 130 |
| Widows Creek | 4 | 1 | 2.5 | 377 | 364 | 245 | 360 |
| | 6 | 2 | 2.2 | 333 | 398 | 569 | 439 |
| | 10 | 2 | 2.4 | 316 | 353 | 440 | 418 |
| | 5 | 2 | 3.4 | 304 | 294 | 257 | 302 |
| | 9 | 2 | 4.1 | 301 | 247 | 261 | 270 |
| | 3 | 2 | 4.8 | 155 | 230 | 427 | 237 |
| | 8 | 2 | 5.2 | 138 | 207 | 235 | 226 |
| | 1 | 2 | 6.5 | 136 | 187 | 220 | 185 |
| | 2 | 3 | 6.0 | 125 | 197 | 202 | 202 |

Table 8

SUMMARY - CALCULATED AND OBSERVED PLUME RISE VALUES

BY WIND SPEED AND STABILITY CLASSIFICATION

| Formula | Stability Class | Wind Speed (m./sec.) | Percent of Observed Rise: Observations > 100% No. | Max. | Avg. | Observations ≤ 100% No. | Min. | Avg. | Total Avg. |
|---|---|---|---|---|---|---|---|---|---|
| CONCAWE | 1 | > 3 | 3 | 171 | 151 | 1 | 90 | 90 | 136 |
| | | ≤ 3 | 0 | - | - | 1 | 97 | 97 | 97 |
| | 2 | > 3 | 14 | 162 | 127 | 20 | 56 | 85 | 103 |
| | | ≤ 3 | 8 | 140 | 115 | 5 | 67 | 76 | 100 |
| | 3 | > 3 | 7 | 159 | 138 | 8 | 55 | 79 | 107 |
| | | ≤ 3 | 0 | - | - | 1 | 96 | 96 | 96 |
| | Total | | 32 | 171 | 129 | 36 | 55 | 83 | 105 |
| Csanady | 1 | > 3 | 3 | 144 | 131 | 1 | 71 | 71 | 116 |
| | | ≤ 3 | 0 | - | - | 1 | 95 | 95 | 95 |
| | 2 | > 3 | 13 | 164 | 130 | 21 | 59 | 85 | 102 |
| | | ≤ 3 | 8 | 158 | 126 | 5 | 78 | 85 | 110 |
| | 3 | > 3 | 9 | 162 | 131 | 6 | 55 | 74 | 108 |
| | | ≤ 3 | 1 | 107 | 107 | 0 | - | - | 107 |
| | Total | | 34 | 164 | 129 | 34 | 55 | 84 | 106 |
| Lucas, Moore, and Spurr | 1 | > 3 | 3 | 129 | 115 | 1 | 76 | 76 | 106 |
| | | ≤ 3 | 0 | - | - | 1 | 65 | 65 | 65 |
| | 2 | > 3 | 18 | 315 | 169 | 16 | 52 | 83 | 128 |
| | | ≤ 3 | 6 | 260 | 151 | 7 | 53 | 76 | 111 |
| | 3 | > 3 | 8 | 162 | 130 | 7 | 58 | 76 | 105 |
| | | ≤ 3 | 1 | 125 | 125 | 0 | - | - | 125 |
| | Total | | 36 | 315 | 149 | 32 | 53 | 79 | 117 |

Table 9

OBSERVED AND CALCULATED PLUME RISE - MULTISTACK OPERATION

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | No. of Stacks Operating | Degrees Off Line of Stacks | Observed Plume Rise (meters) | Calculated Plume Rise (meters) Optimized Formulas CONCAWE | Csanady |
|---|---|---|---|---|---|---|---|---|
| Paradise | 44 | 1 | 5.9 | 2 | 42.1 | 245 | 238 | 210 |
| | 14 | 1 | 8.8 | 2 | 61.9 | 201 | 174 | 151 |
| | 47 | 1 | 10.3 | 2 | 10.3 | 143 | 161 | 136 |
| | 46 | 2 | 3.7 | 2 | 26.2 | 414 | 333 | 350 |
| | 45 | 2 | 4.2 | 2 | 38.0 | 364 | 302 | 305 |
| | 33 | 2 | 4.4 | 2 | 69.3 | 328 | 278 | 288 |
| | 32 | 2 | 4.8 | 2 | 62.9 | 258 | 263 | 259 |
| | 34 | 2 | 5.5 | 2 | 62.0 | 370 | 240 | 243 |
| | 37 | 2 | 5.8 | 2 | 31.6 | 305 | 247 | 240 |
| | 36 | 2 | 6.6 | 2 | 20.2 | 283 | 228 | 211 |
| | 35 | 2 | 6.8 | 2 | 8.7 | 279 | 224 | 204 |
| | 16 | 2 | 7.2 | 2 | 30.1 | 251 | 191 | 194 |
| | 15 | 2 | 7.7 | 2 | 56.9 | 226 | 192 | 185 |
| | 17 | 2 | 7.8 | 2 | 5.6 | 127 | 185 | 177 |
| | 50 | 2 | 8.5 | 2 | 8.2 | 125 | 184 | 176 |
| | 18 | 2 | 8.6 | 2 | 14.7 | 183 | 173 | 169 |
| | 48 | 2 | 8.6 | 2 | 11.8 | 185 | 182 | 169 |
| | 49 | 2 | 8.6 | 2 | 12.3 | 233 | 182 | 172 |
| | 20 | 2 | 9.5 | 2 | 25.5 | 176 | 161 | 154 |
| | 19 | 3 | 7.7 | 2 | 16.1 | 237 | 187 | 184 |

Table 9 (continued)

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | No. of Stacks Operating | Degrees Off Line of Stacks | Observed Plume Rise (meters) | Calculated Plume Rise (meters) Optimized Formulas CONCAWE | Csanady |
|---|---|---|---|---|---|---|---|---|
| Gallatin | 33 | 2 | 1.2 | 2 | 69.8 | 529 | 442 | 607 |
| | 32 | 2 | 7.4 | 2 | 82.3 | 96 | 126 | 146 |
| | 37 | 2 | 10.5 | 2 | 17.5 | 122 | 104 | 105 |
| | 38 | 2 | 11.8 | 2 | 12.6 | 128 | 96 | 103 |
| | 35 | 3 | 5.1 | 2 | 41.0 | 138 | 166 | 203 |
| Shawnee | 2 | 2 | 2.5 | 9 | 34.2 | 266 | 351 | 476 |
| | 1 | 2 | 2.7 | 9 | 54.6 | 546 | 300 | 405 |
| | 3 | 2 | 3.8 | 9 | 38.0 | 236 | 258 | 338 |
| | 10 | 2 | 6.3 | 8 | 68.2 | 126 | 140 | 173 |
| | 7 | 2 | 7.0 | 8 | 80.5 | 88 | 118 | 142 |
| | 12 | 2 | 8.8 | 8 | 52.2 | 68 | 129 | 147 |
| | 4 | 3 | 2.4 | 9 | 55.8 | 493 | 316 | 436 |
| | 11 | 3 | 6.4 | 8 | 88.0 | 79 | 113 | 142 |
| | 8 | 3 | 8.5 | 8 | 75.3 | 53 | 109 | 129 |

Table 9 (continued)

| Steam Plant | Obs. No. | Stability Class | Wind Speed (m./sec.) | No. of Stacks Operating | Degrees Off Line of Stacks | Observed Plume Rise (meters) | Calculated Plume Rise (meters) Optimized Formulas CONCAWE | Csanady |
|---|---|---|---|---|---|---|---|---|
| Johnsonville | 4 | 1 | 1.2 | 2 | 19.5 | 492 | 556 | 624 |
| | 5 | 1 | 1.3 | 2 | 25.3 | 393 | 525 | 570 |
| | 1 | 1 | 2.7 | 2 | 5.5 | 212 | 309 | 308 |
| | 11 | 1 | 5.1 | 2 | 87.1 | 185 | 171 | 165 |
| | 8 | 1 | 6.8 | 2 | 21.5 | 119 | 165 | 141 |
| | 6 | 2 | 1.1 | 2 | 15.4 | 466 | 592 | 711 |
| | 7 | 2 | 1.8 | 2 | 13.9 | 661 | 421 | 493 |
| | 10 | 2 | 1.9 | 2 | 30.0 | 498 | 380 | 468 |
| | 13 | 2 | 1.9 | 2 | 81.8 | 414 | 341 | 428 |
| | 2 | 2 | 2.3 | 2 | 16.0 | 375 | 344 | 394 |
| | 12 | 2 | 5.2 | 2 | 86.1 | 249 | 169 | 181 |
| | 9 | 2 | 6.1 | 2 | 20.3 | 293 | 178 | 176 |
| | 3 | 3 | 1.0 | 2 | 13.0 | 720 | 614 | 792 |
| Colbert | 1 | 1 | 1.4 | 3 | 8.6 | 403 | 461 | 543 |
| | 9 | 1 | 4.0 | 3 | 79.3 | 151 | 176 | 176 |
| | 7 | 1 | 4.2 | 3 | 34.7 | 233 | 182 | 189 |
| | 10 | 1 | 4.5 | 4 | 22.8 | 301 | 178 | 205 |
| | 3 | 1 | 4.8 | 3 | 31.6 | 219 | 177 | 184 |
| | 6 | 1 | 5.3 | 3 | 35.4 | 164 | 154 | 137 |
| | 2 | 2 | 1.9 | 3 | 10.4 | 430 | 373 | 450 |
| | 8 | 2 | 3.2 | 3 | 34.7 | 365 | 219 | 276 |
| | 4 | 2 | 3.8 | 3 | 19.7 | 311 | 211 | 262 |
| | 5 | 3 | 4.8 | 3 | 17.1 | 340 | 180 | 219 |

TENNESSEE VALLEY AUTHORITY
Division of Health and Safety

# APPENDIX B

## FIGURES

Muscle Shoals, Alabama
September 1968

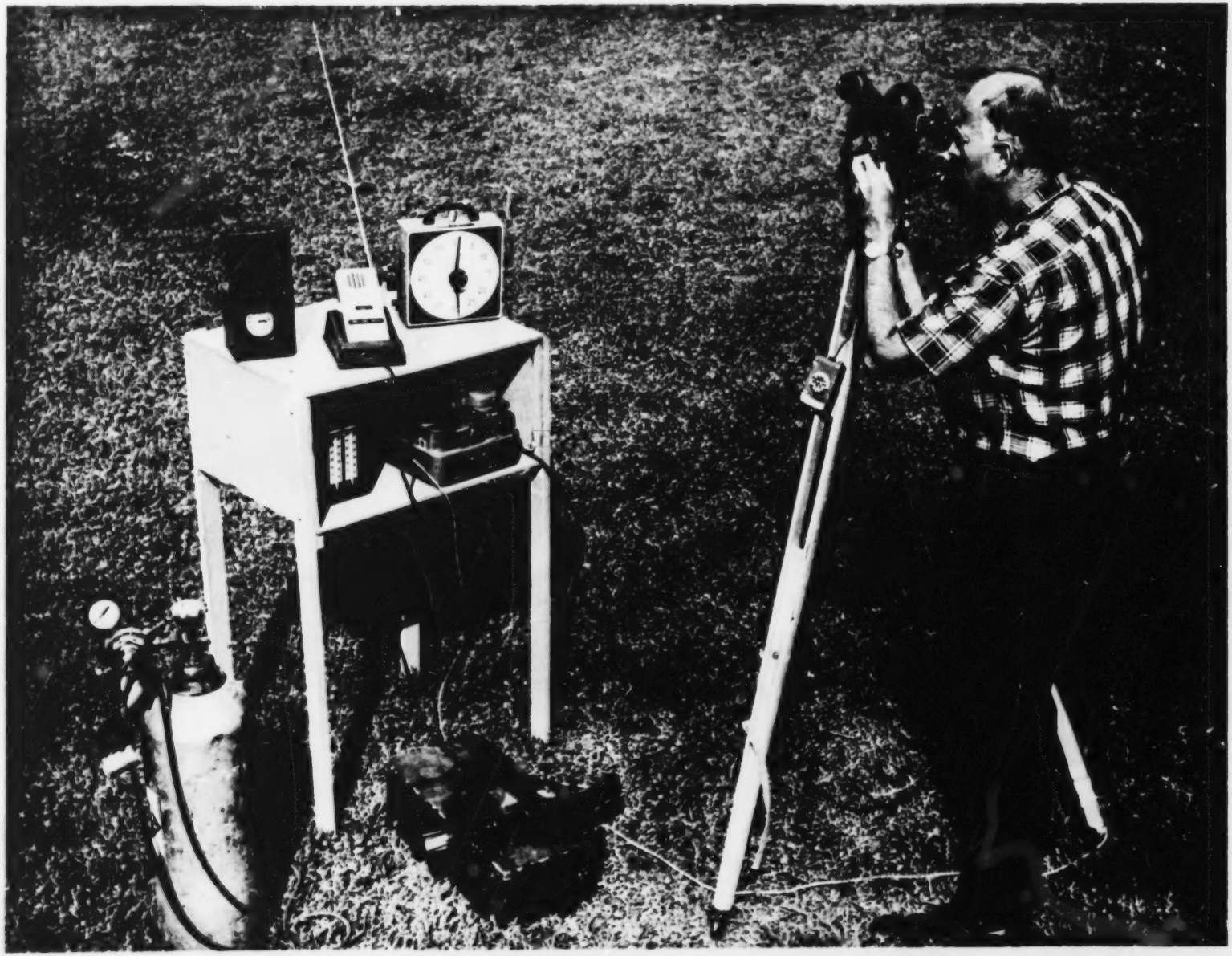


Figure 1. INSTRUMENTATION, PRIMARY PIBAL STATION

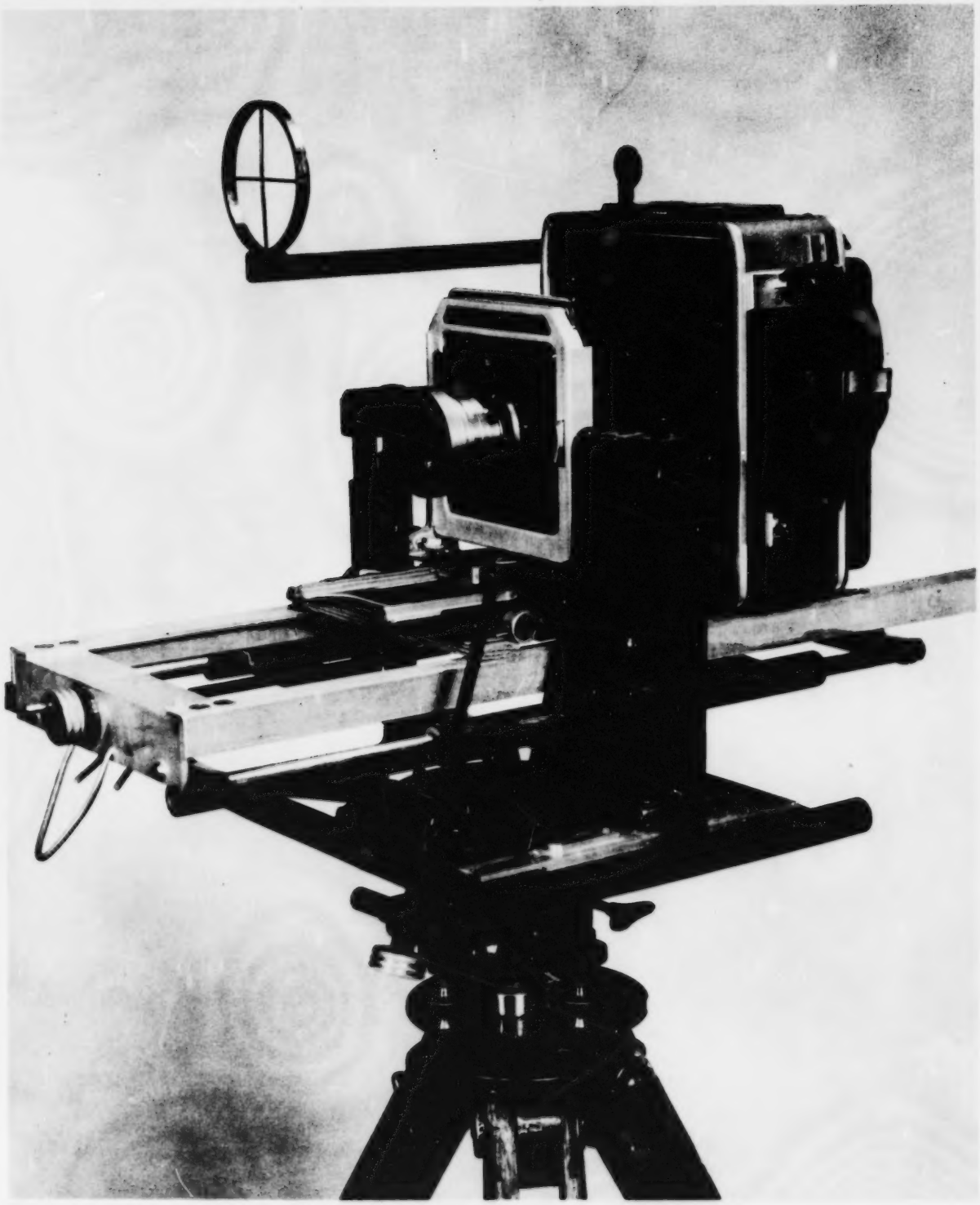


Figure 2. CAMERA WITH SPECIAL TRANSIT MOUNT

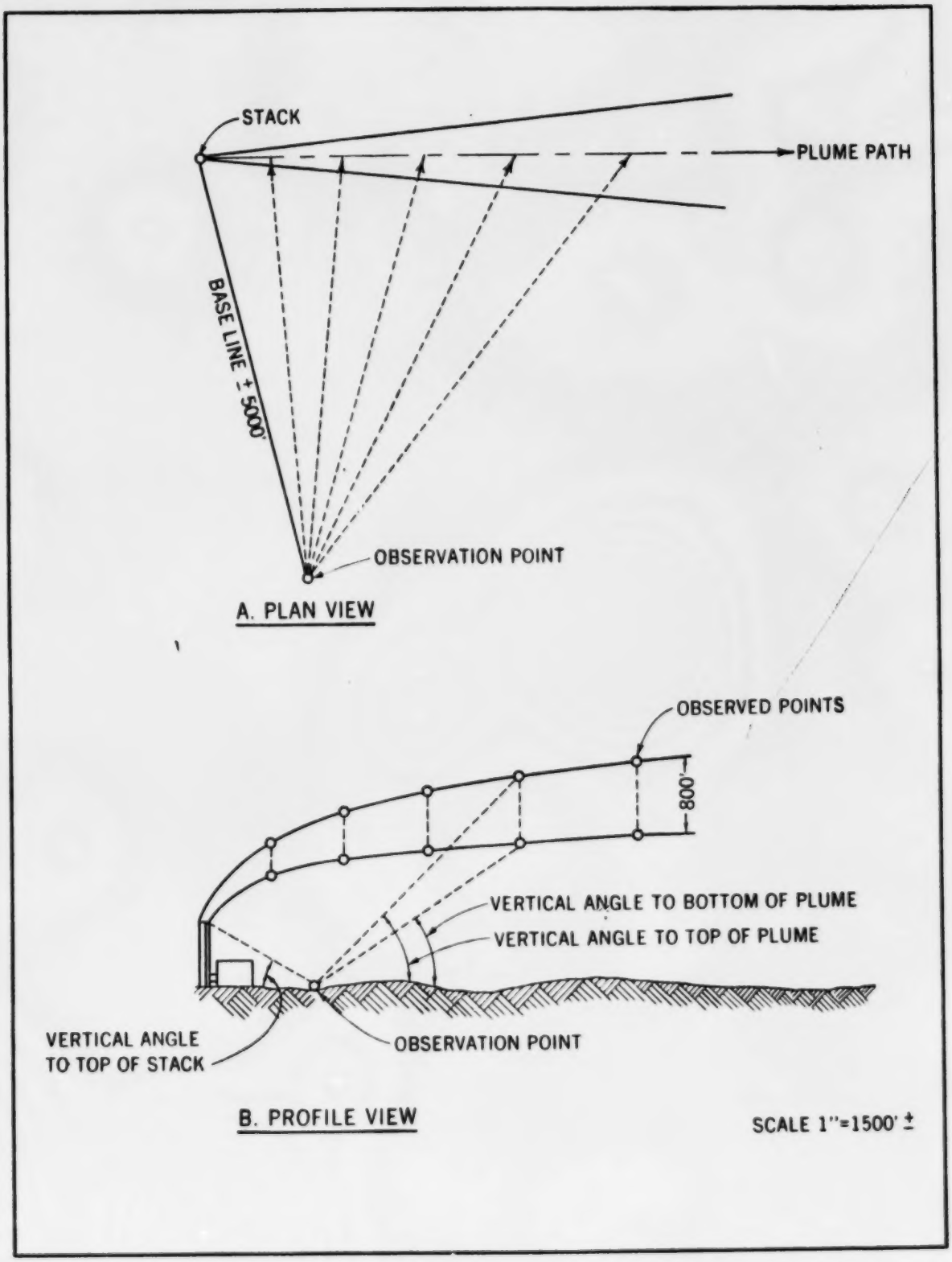



Figure 3. PLUME OBSERVATIONAL PLAN BY MODIFIED TRANSIT

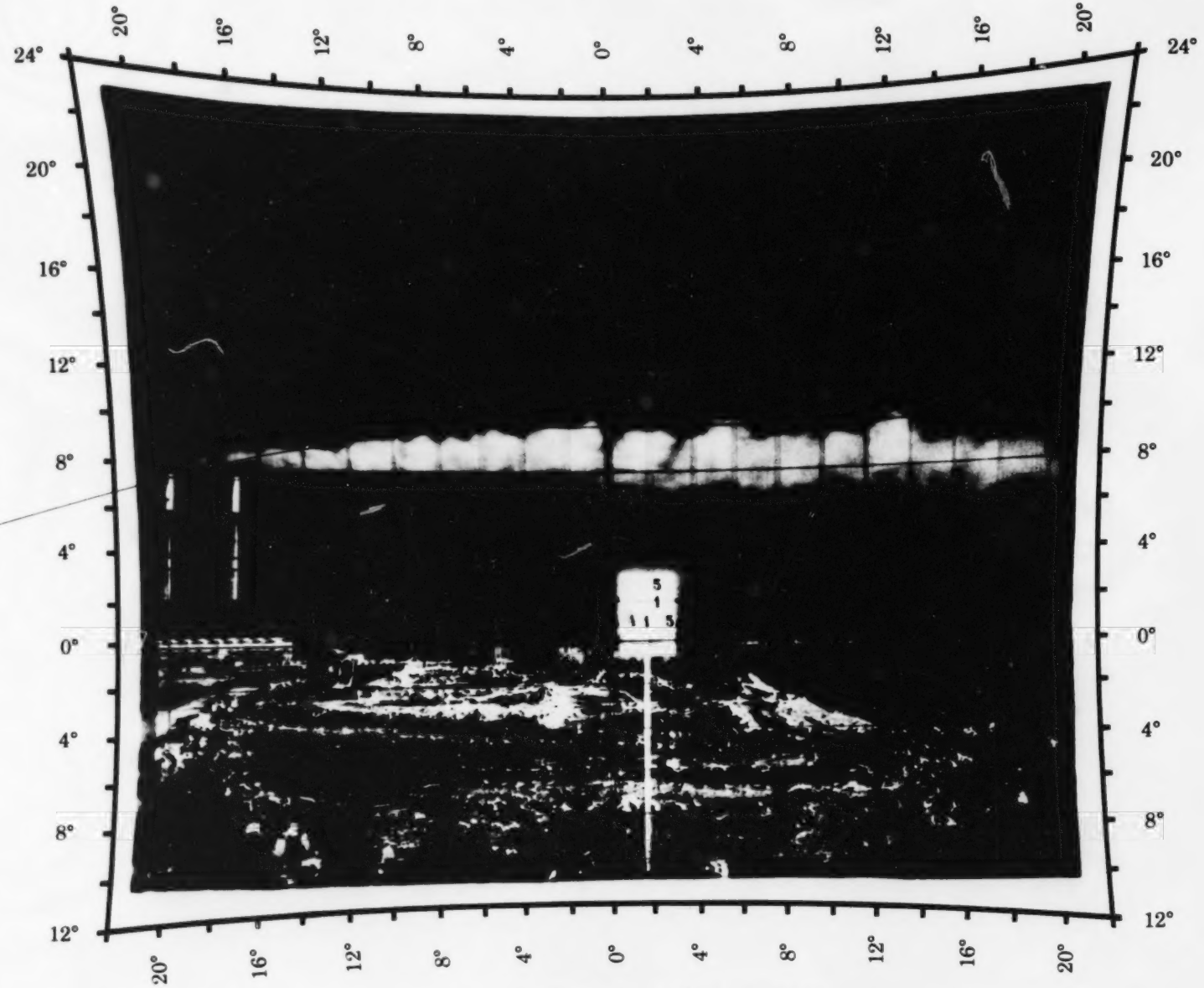
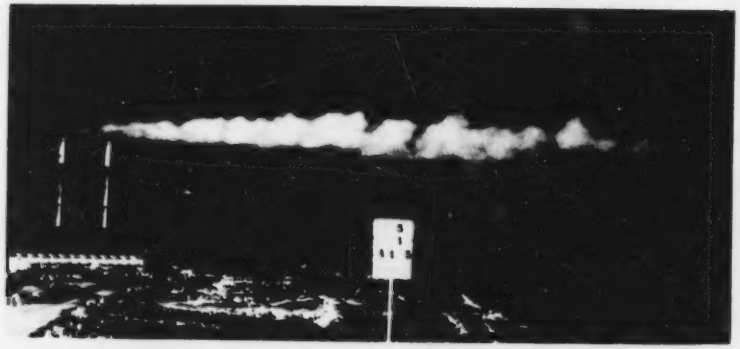
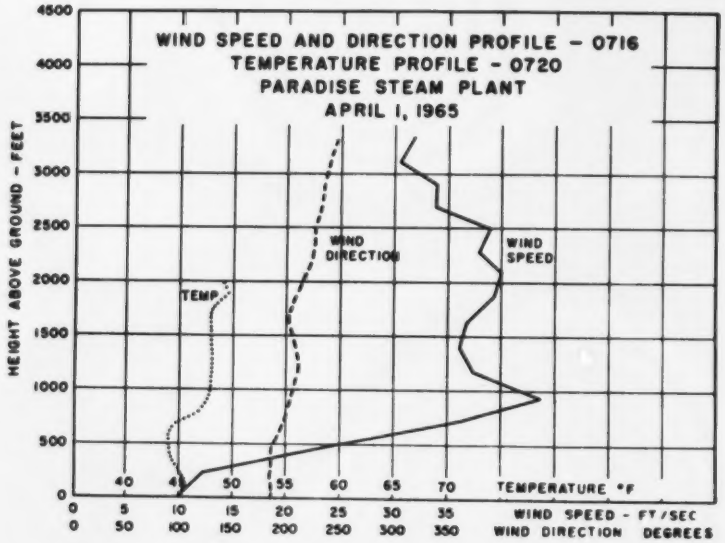


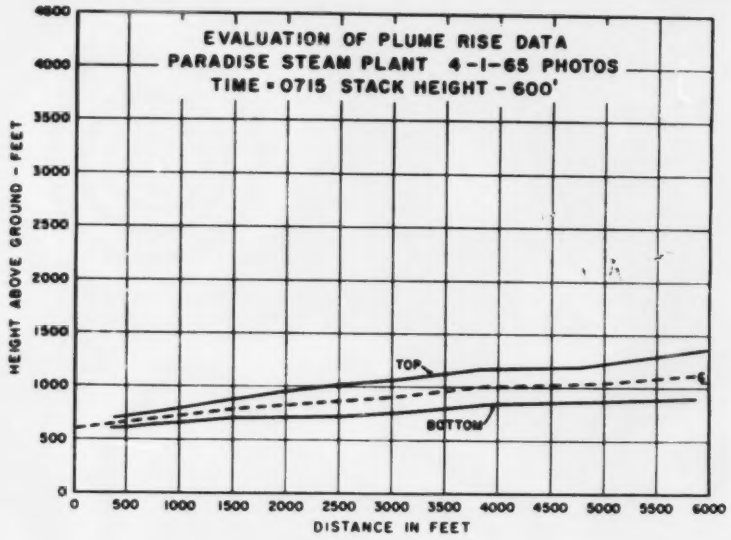

Figure 4. TEMPLATE ON PLUME PHOTOGRAPH



PLUME PHOTOGRAPH – 0715




WIND SPEED, DIR. & TEMP. PROFILE 0716-0720




PLUME PROFILE – 0715



Figure 5. DATA FROM TYPICAL DAY OF FIELD OPERATION, APRIL 1, 1965 PARADISE STEAM PLANT

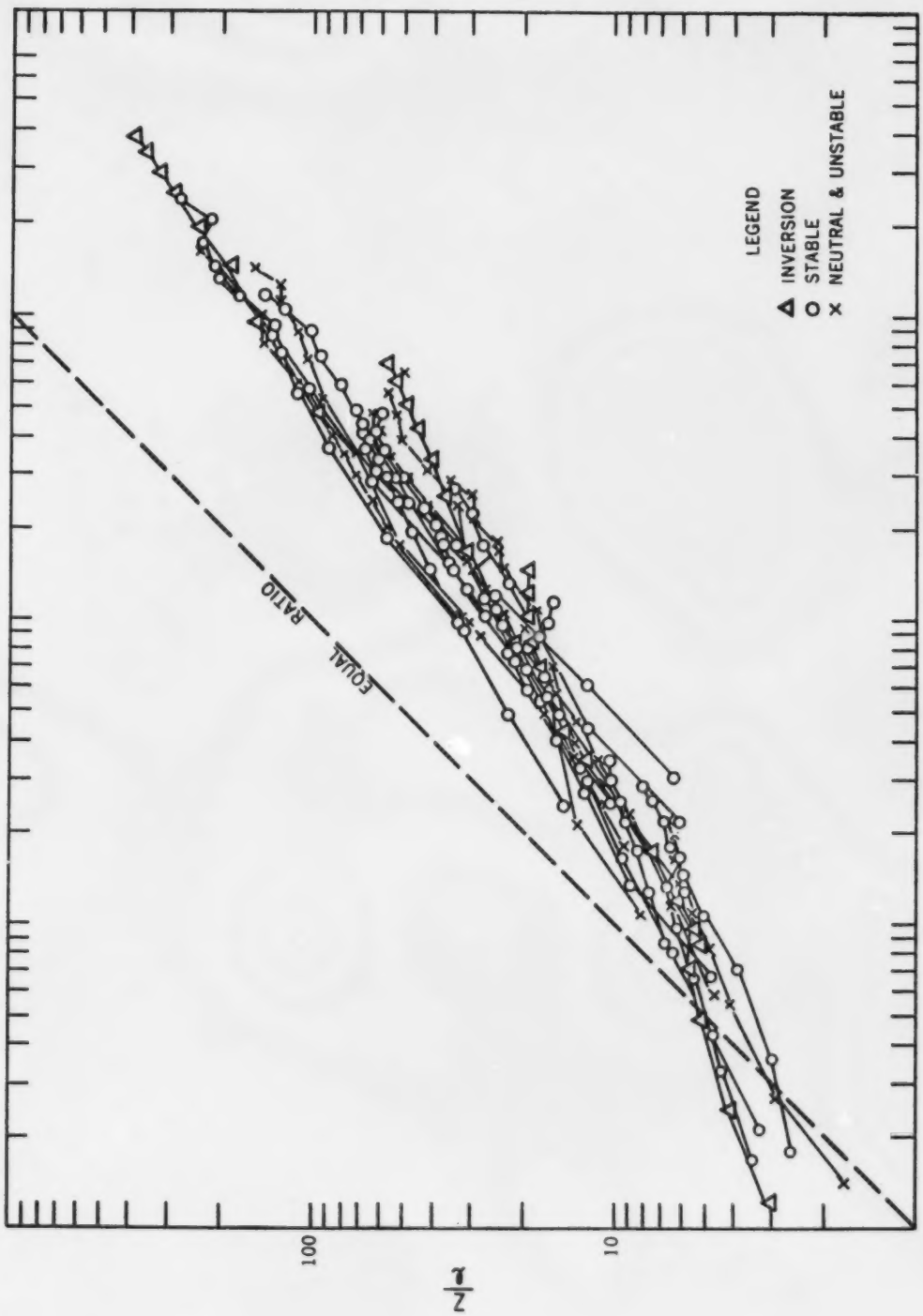



Figure 6. INITIAL PLUME RISE PHASE $\frac{Z}{L}$ VS $\frac{X}{L}$

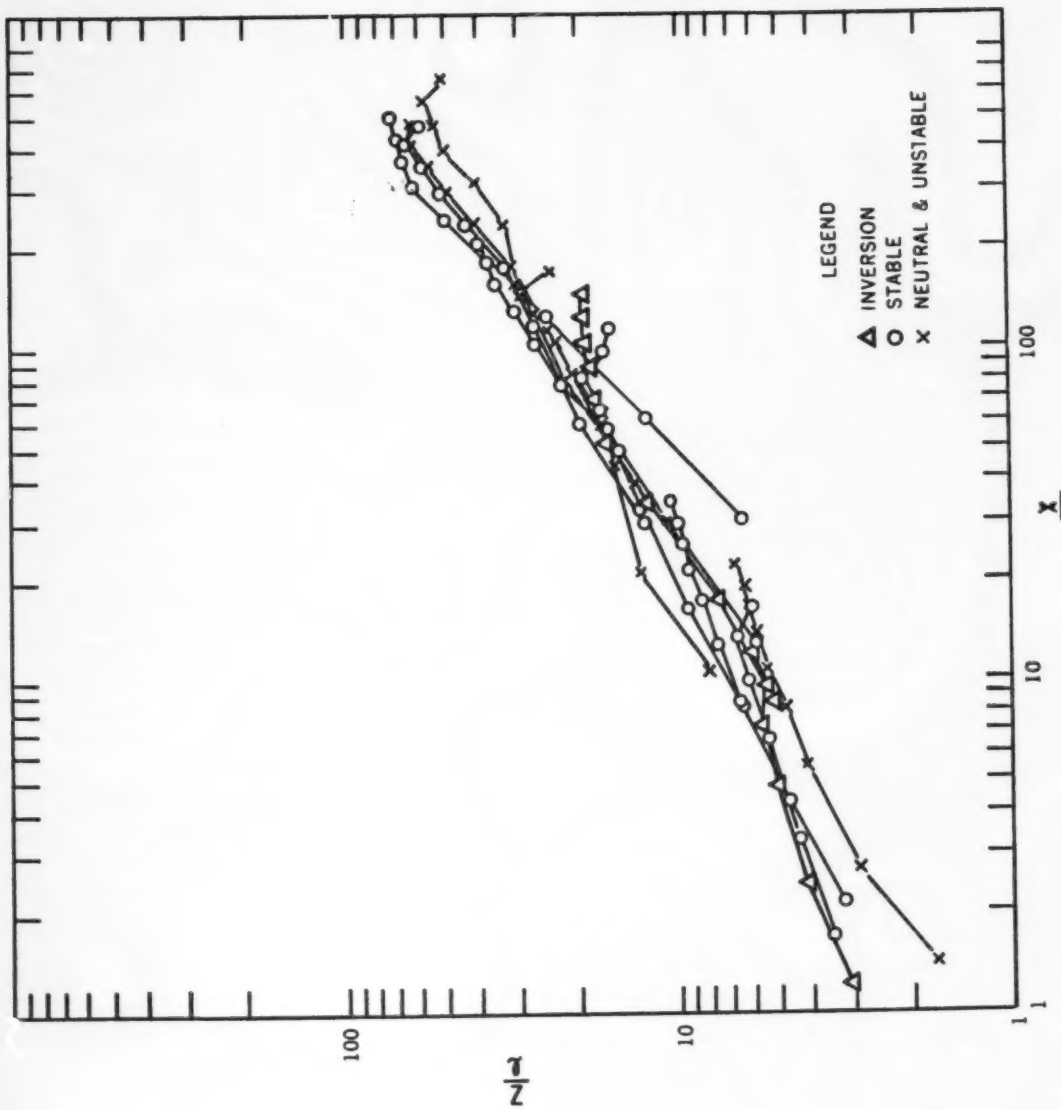



Figure 7. INITIAL PLUME RISE PHASE $\frac{Z}{L}$ VS $\frac{X}{L}$

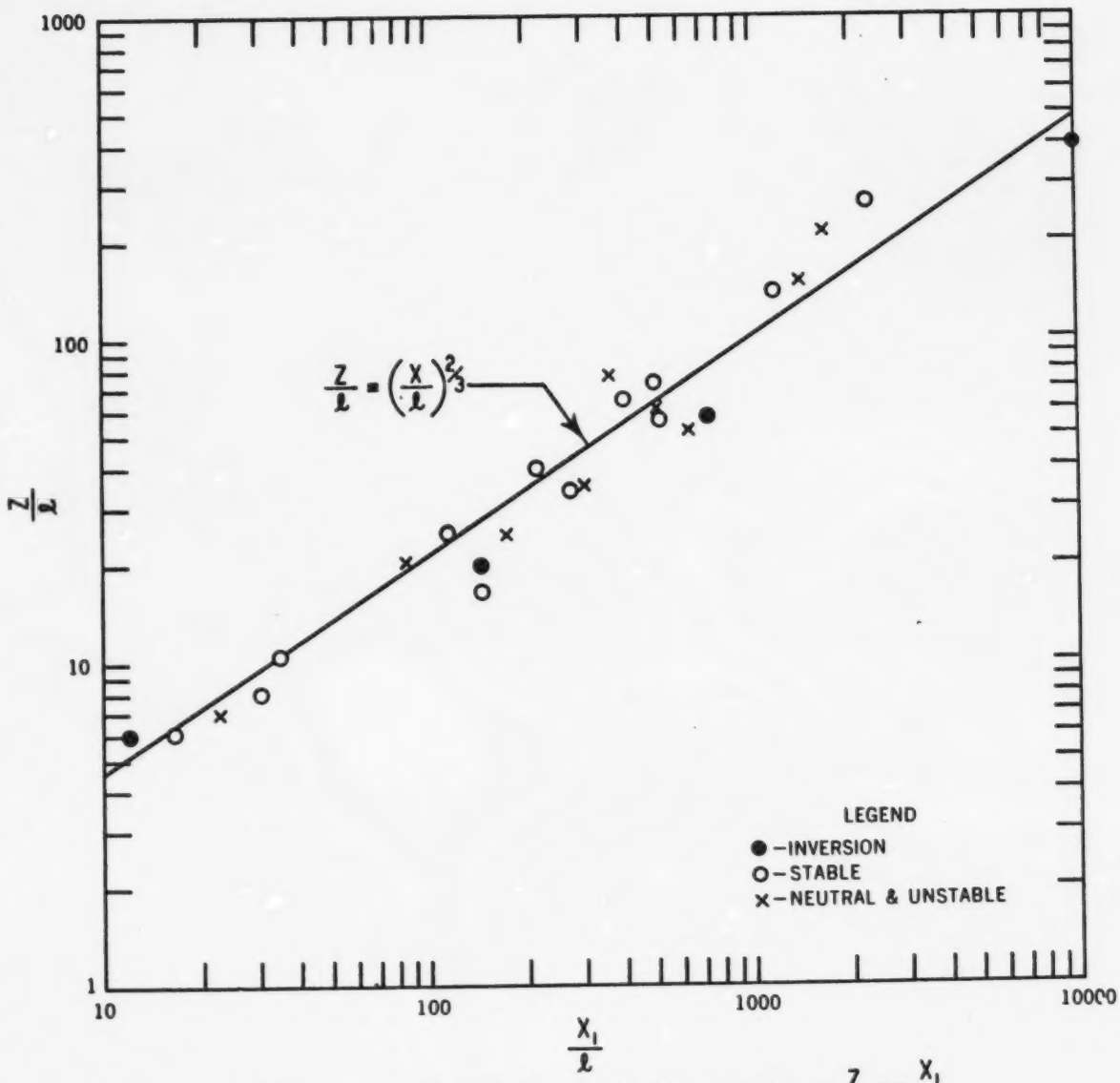



Figure 8. END OF INITIAL PLUME RISE PHASE – $\frac{Z}{\ell}$ VS $\frac{X_1}{\ell}$

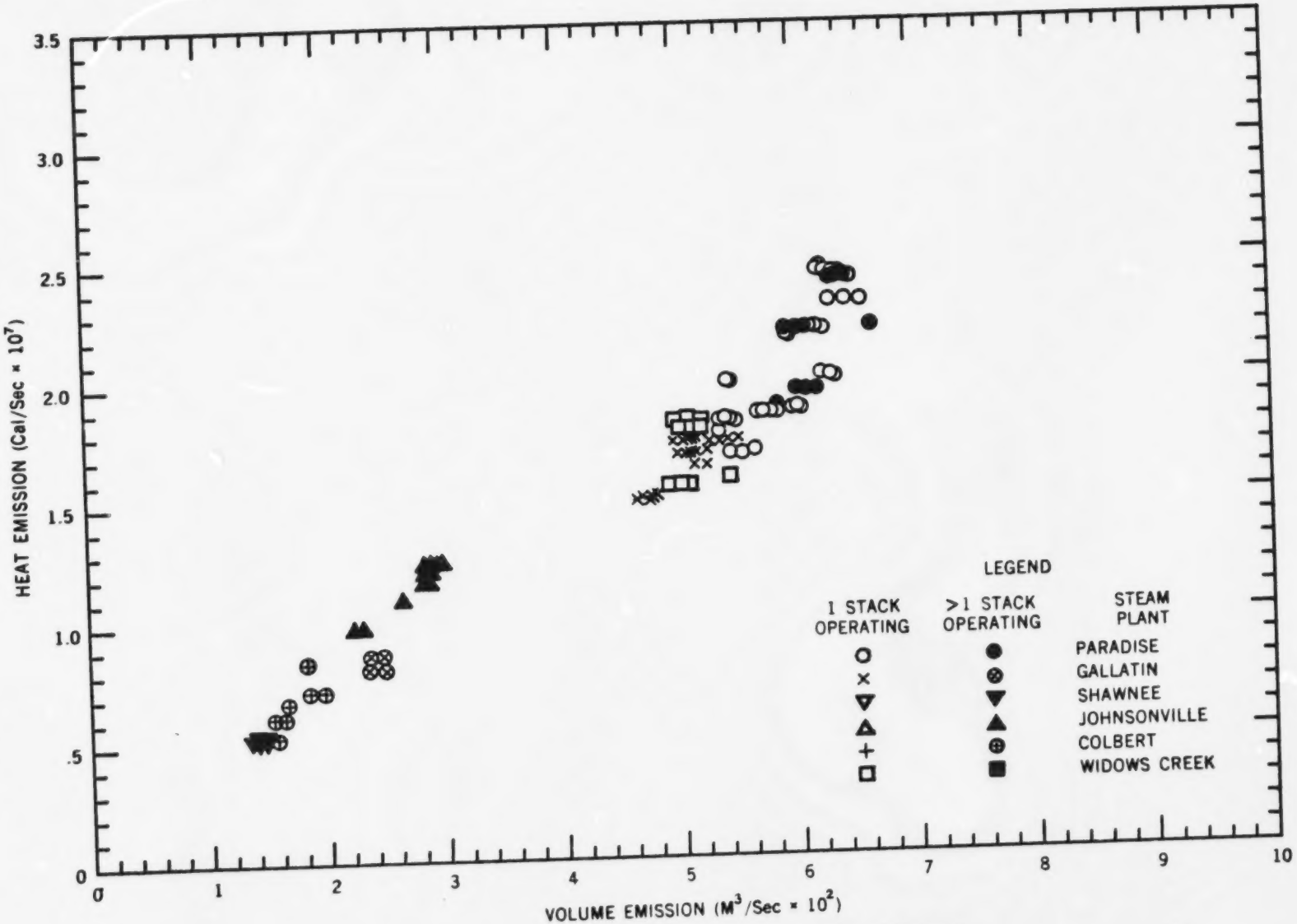



**Figure 9. HEAT EMISSION VS VOLUME EMISSION**

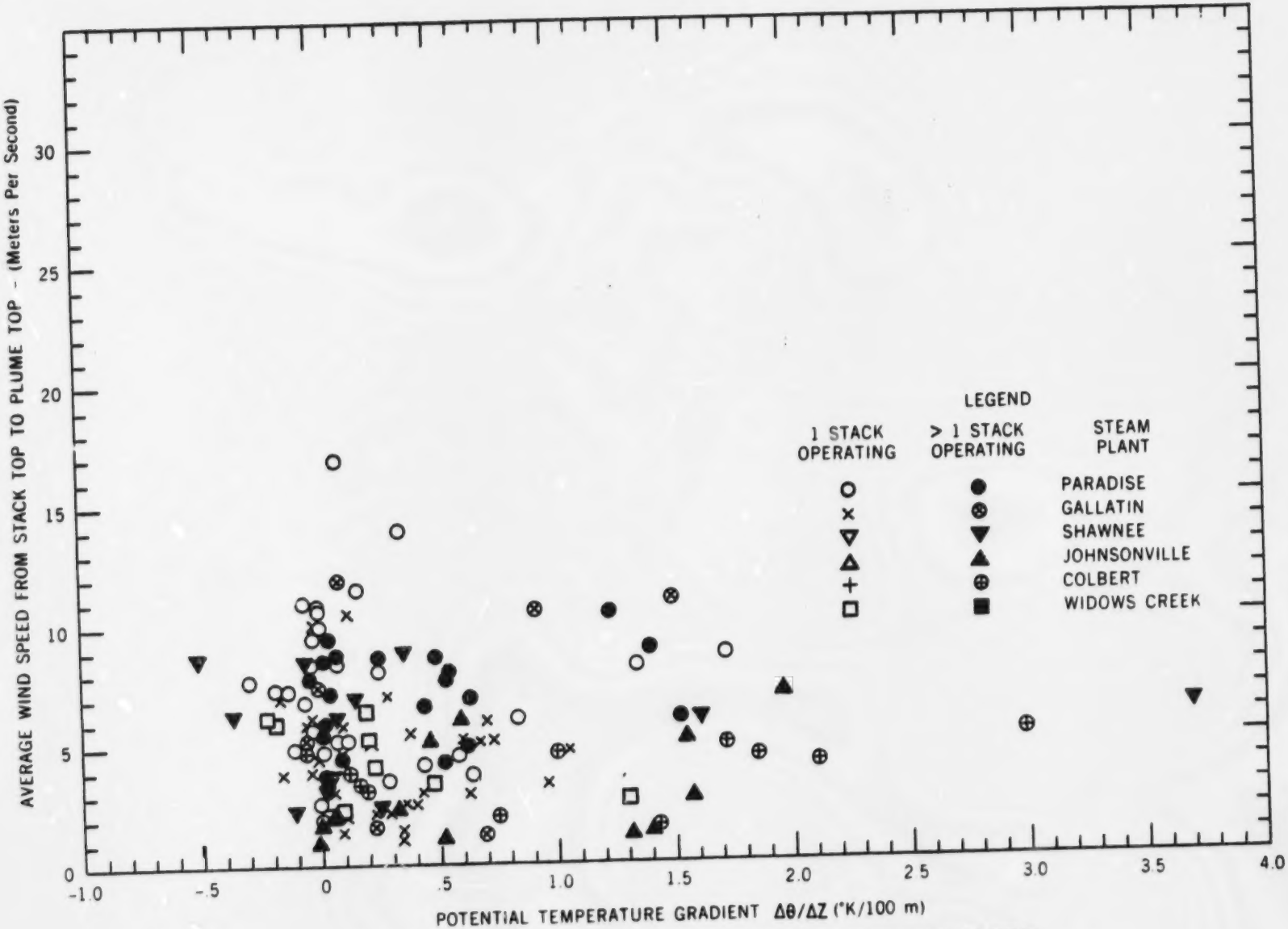



Figure 10. WIND SPEED VS POTENTIAL TEMPERATURE GRADIENT

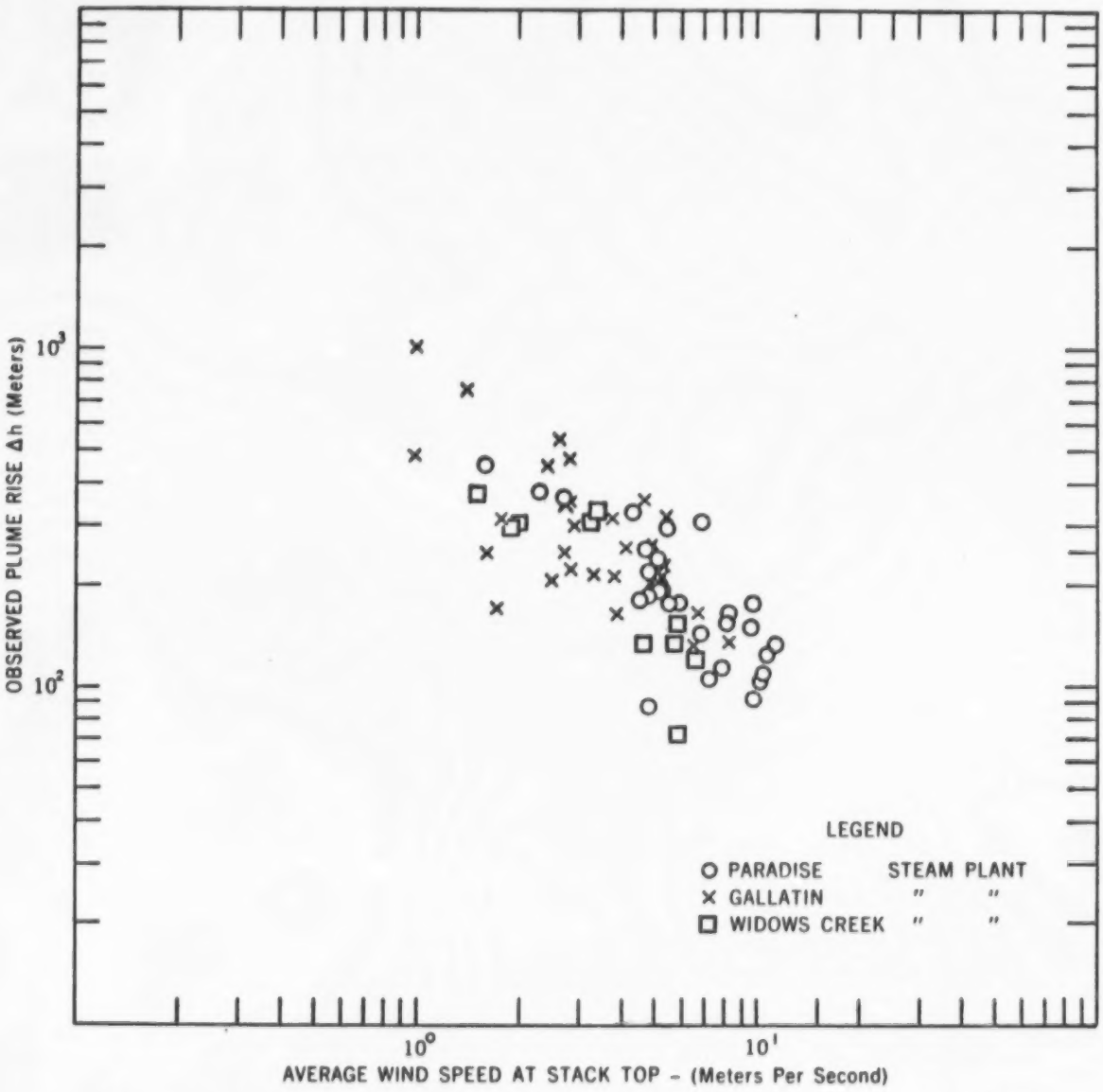



Figure 12. OBSERVED PLUME RISE VS AVERAGE WIND SPEED AT STACK TOP

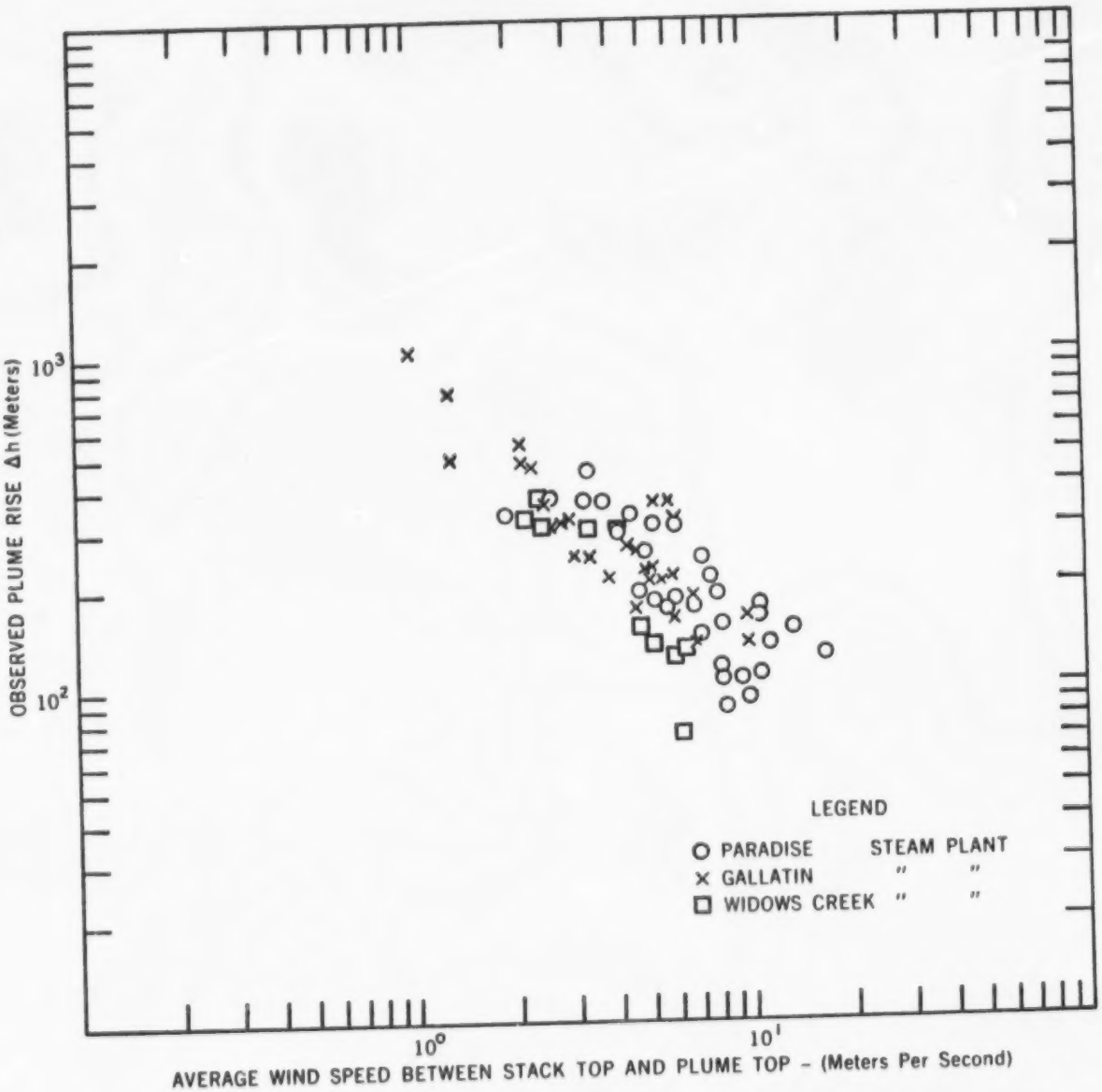



Figure 13. OBSERVED PLUME RISE VS AVERAGE WIND SPEED BETWEEN STACK TOP AND PLUME TOP

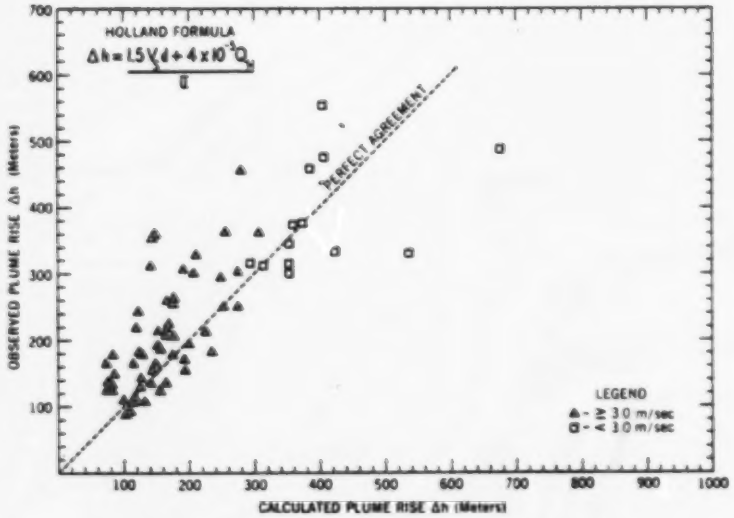



Figure 14. RELATION – OBSERVED AND CALCULATED PLUME RISE

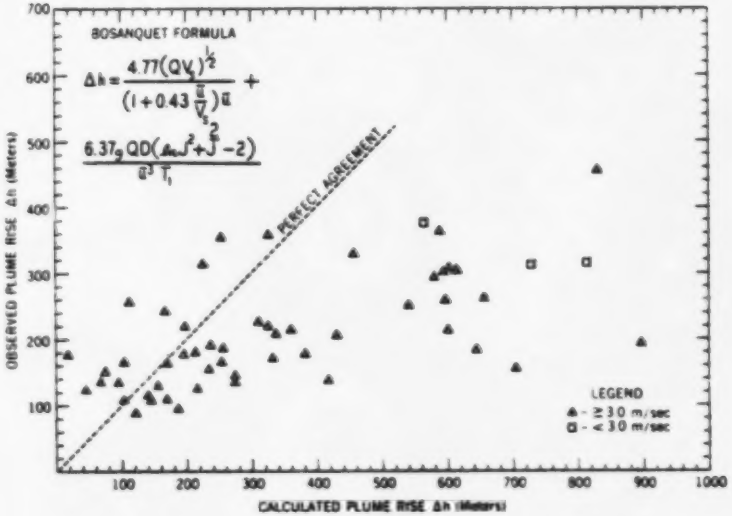



Figure 15. RELATION – OBSERVED AND CALCULATED PLUME RISE

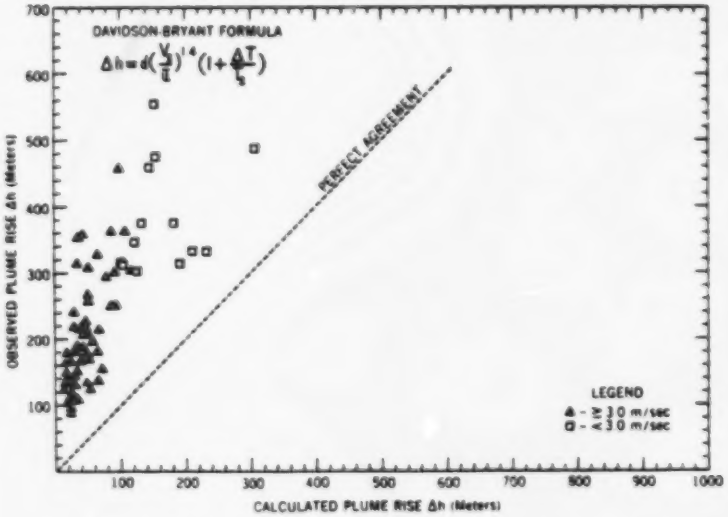



Figure 16. RELATION – OBSERVED AND CALCULATED PLUME RISE

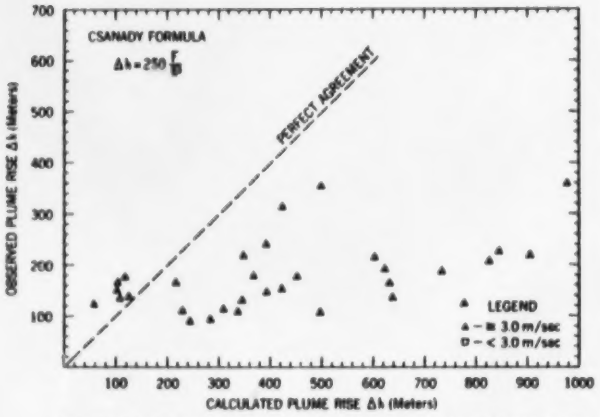



Figure 17. RELATION – OBSERVED AND CALCULATED PLUME RISE

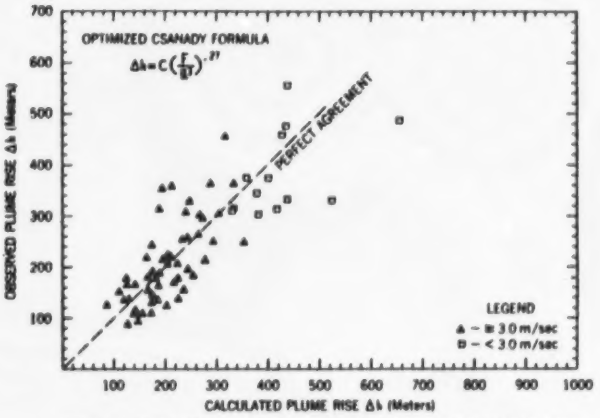



Figure 20. RELATION – OBSERVED AND CALCULATED PLUME RISE

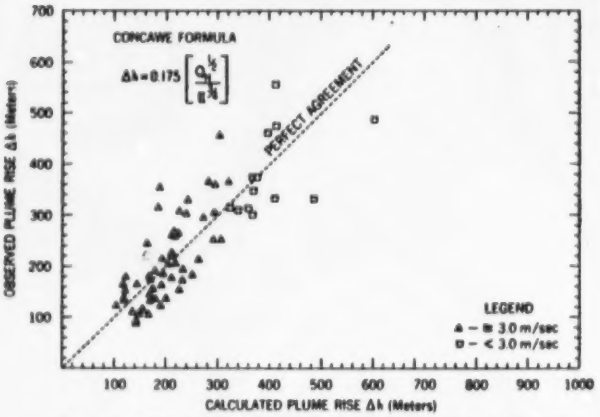



Figure 18. RELATION – OBSERVED AND CALCULATED PLUME RISE

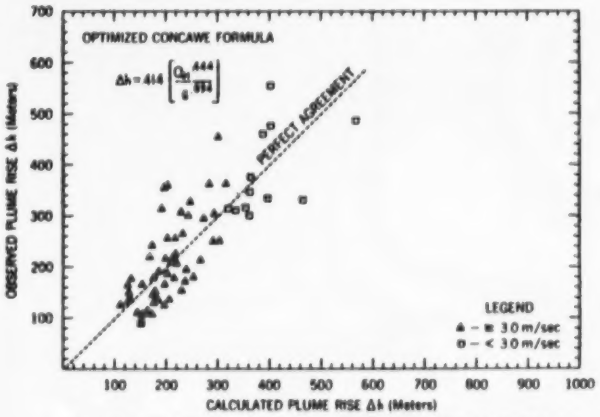



Figure 21. RELATION – OBSERVED AND CALCULATED PLUME RISE

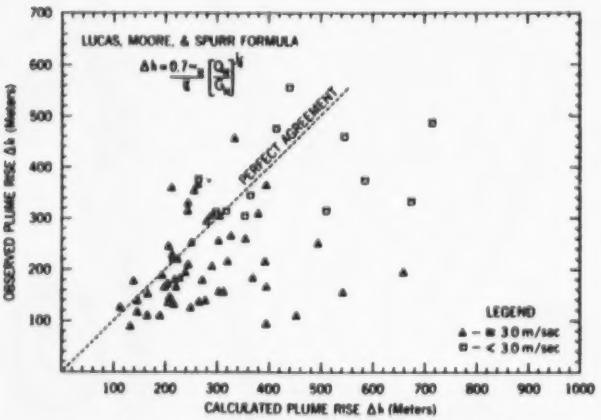

LUCAS, MOORE, & SPURR FORMULA
PERFECT AGREEMENT
LEGEND
▲ – ≥ 3.0 m/sec
□ – < 3.0 m/sec
OBSERVED PLUME RISE Δh (Meters)
CALCULATED PLUME RISE Δh (Meters)

Figure 19. RELATION – OBSERVED AND CALCULATED PLUME RISE

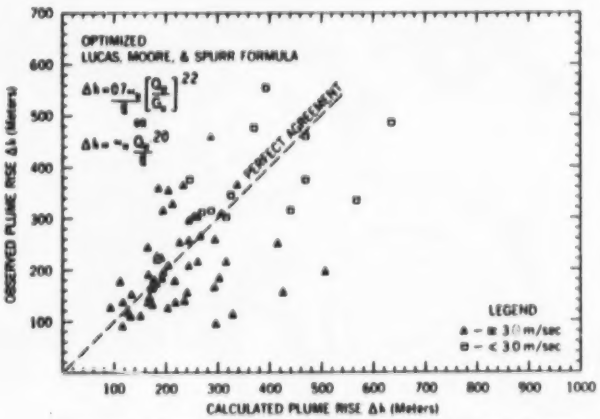



Figure 22. RELATION – OBSERVED AND CALCULATED PLUME RISE

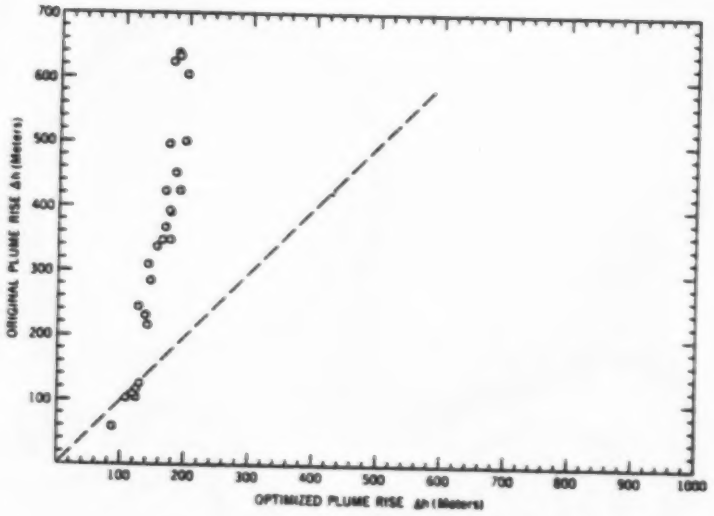



Figure 23. RELATION – CALCULATED PLUME RISE FROM THE ORIGINAL AND OPTIMIZED CSANADY FORMULAS

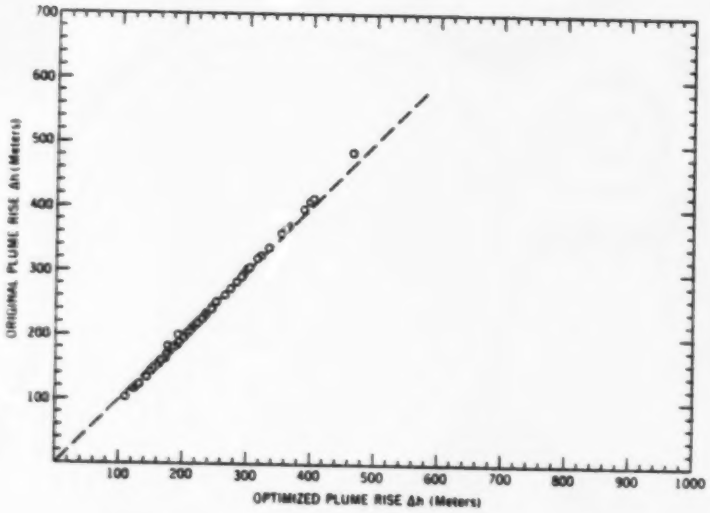



Figure 24. RELATION – CALCULATED PLUME RISE FROM THE ORIGINAL AND OPTIMIZED CONCAWE FORMULAS

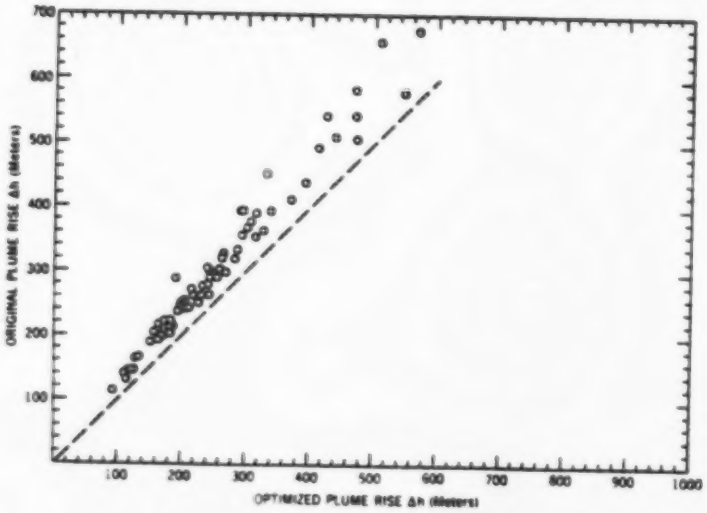



Figure 25. RELATION – CALCULATED PLUME RISE FROM THE ORIGINAL AND OPTIMIZED LUCAS, MOORE, AND SPURR FORMULAS

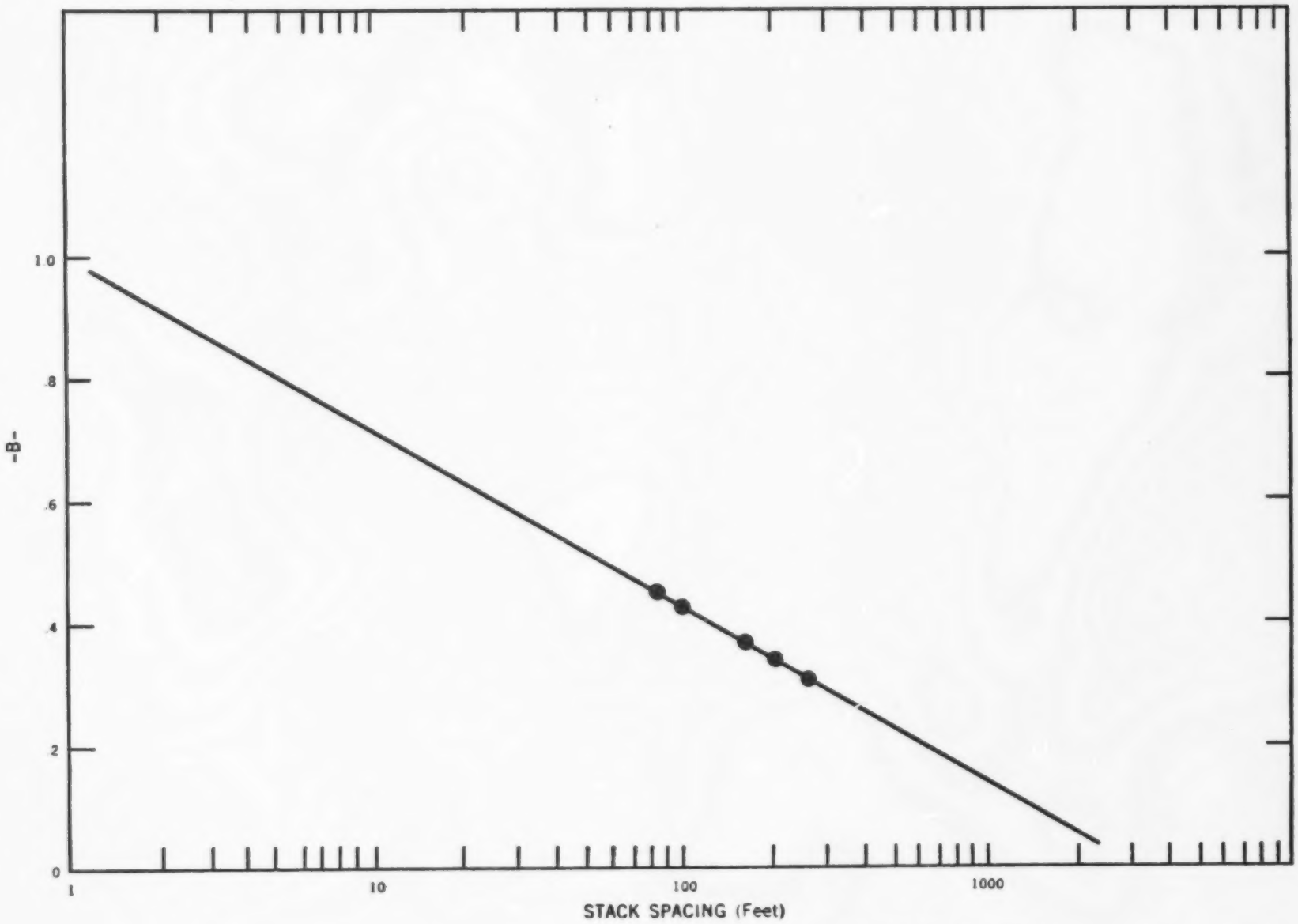



Figure 26. VARIATION OF THE VALUE OF B WITH STACK SPACING

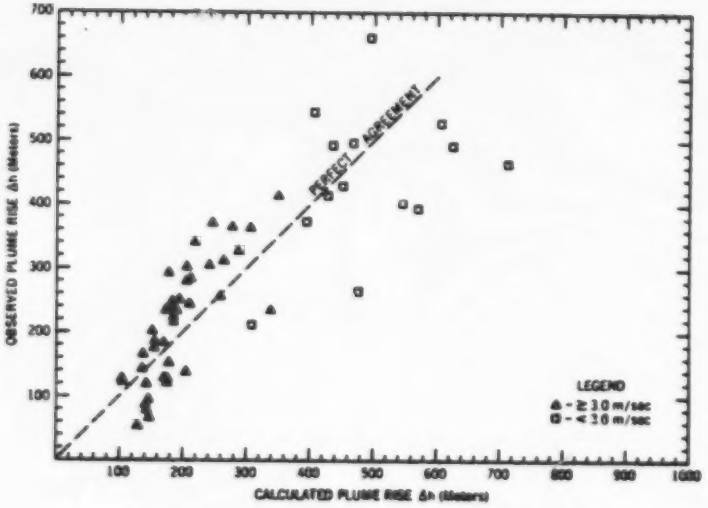



Figure 27. RELATION – OBSERVED AND CALCULATED PLUME RISE
CSANADY FORMULA – MULTISTACK

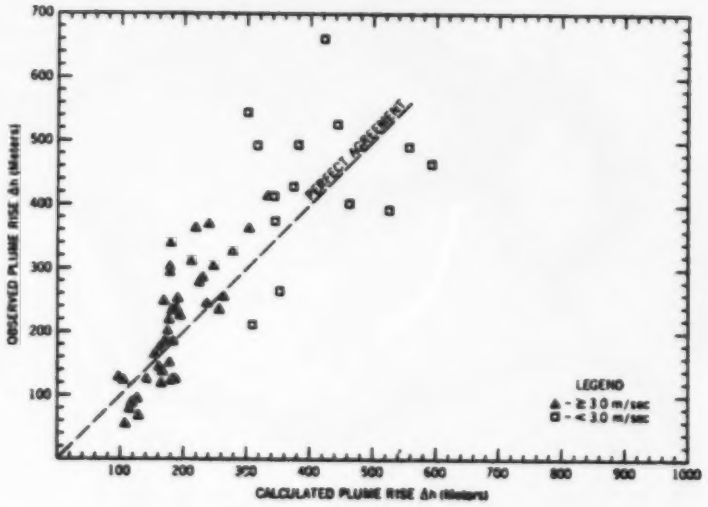



Figure 28. RELATION – OBSERVED AND CALCULATED PLUME RISE
CONCAWE FORMULA – MULTISTACK

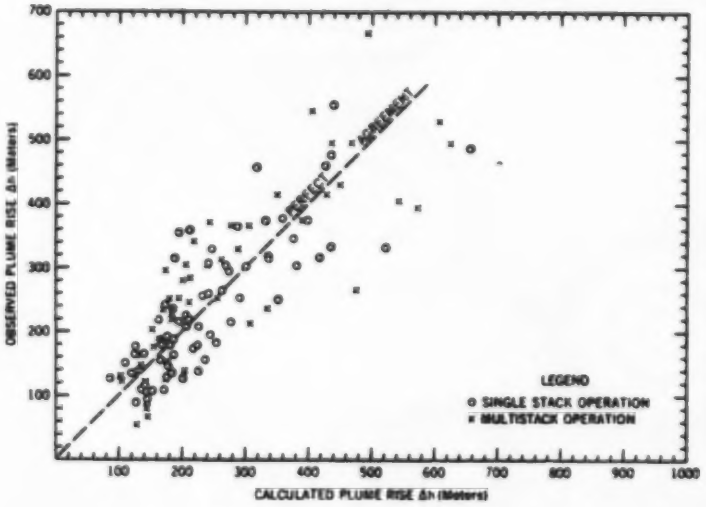



Figure 29. RELATION – OBSERVED AND CALCULATED PLUME RISE
CSANADY FORMULAS – SINGLE AND MULTISTACK

TENNESSEE VALLEY AUTHORITY
Division of Health and Safety

# APPENDIX C

## FORMULAS

Muscle Shoals, Alabama
September 1968

## HOLLAND PLUME RISE FORMULA

$$\Delta h = \frac{1.5\ V_s d + 4 \times 10^{-5}\ Q_H}{\overline{u}}$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (meters)

$V_s$ = stack gas exit velocity (meters per second)

$d$ = stack exit diameter (meters)

$Q_H$ = heat emission (calories per second)

$\overline{u}$ = mean horizontal wind speed (meters per second)

## BOSANQUET, ET AL, PLUME RISE FORMULA

### IF G > 0

$$\Delta h = \frac{4.77\ (Q\ V_s)^{1/2}}{\left(1 + 0.43\ \frac{\overline{u}}{V_s}\right)\overline{u}} + \frac{6.37\ g\ QD\left(\ln J^2 + \frac{2}{J} - 2\right)}{\overline{u}^3 T_1}$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (feet)

$Q$ = stack gas emission rate converted to temperature $T_1$ (cubic feet per second)

$V_s$ = stack gas exit velocity (feet per second)

$\overline{u}$ = mean horizontal wind speed (feet per second)

$g$ = acceleration due to gravity (feet per second$^2$)

$D$ = difference between ambient temperature and stack gas temperature at stack top (°K)

$$J = \frac{\overline{u}^2}{(Q\ V_s)^{1/2}}\left[0.43\left(\frac{T_1}{gG}\right)^{1/2} - 0.28\ \frac{V_s T_1}{gD}\right] + 1$$

$G$ = change of potential temperature with height from stack top to plume top (°K per foot)

$T_1$ = temperature at which density of flue gases is equal to that of the atmosphere (°K)

## BOSANQUET, ET AL, PLUME RISE FORMULA

### IF $G \leq 0$

$$z = 6.37\, g\, \frac{QD}{\bar{u}^3 T_1}\, Z$$

$$x = 3.57\, \frac{\sqrt{QV_s}}{\bar{u}}\, X$$

where:

$x$ = distance downwind from stack (feet)

$Q$ = stack gas emission rate converted to temperature $T_1$ (cubic feet per second)

$V_s$ = stack gas exit velocity (feet per second)

$\bar{u}$ = mean horizontal wind speed (feet per second)

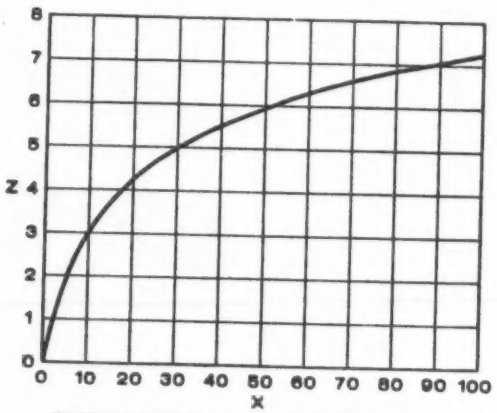
$z$ = predicted rise of the plume above the stack top (feet)

$g$ = acceleration due to gravity (feet per second$^2$)

$D$ = difference between ambient temperature and stack gas temperature at stack top (°K)

$T_1$ = temperature at which density of flue gases is equal to that of the atmosphere (°K)

$G$ = change of potential temperature with height from stack top to plume top (°K per foot)




**THERMAL RISE OF A PLUME SHOWING RELATIONSHIP BETWEEN X AND Z**

## DAVIDSON-BRYANT PLUME RISE FORMULA

$$\Delta h = d\left(\frac{V_s}{\bar{u}}\right)^{1.4}\left(1 + \frac{\Delta T}{T_s}\right)$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (meters)

$d$ = stack exit diameter (meters)

$V_s$ = stack gas exit velocity (meters per second)

$\bar{u}$ = mean horizontal wind speed (meters per second)

$\Delta T$ = temperature difference between exit stack gas and ambient air (°K)

$T_s$ = absolute temperature of stack gas (°K)

## CSANADY PLUME RISE FORMULA

$$\Delta h = 250 \frac{F}{\bar{u}^3}$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (feet)

$F$ = flux due to buoyancy and momentum = $V_s r^2 b$ (feet$^4$ per second$^3$)

$V_s$ = stack gas exit velocity (feet per second)

$r$ = stack exit radius (feet)

$b$ = buoyant acceleration at top of stack = $g \frac{\rho_a - \rho}{\rho}$ (feet per second$^2$)

where:

$\rho$ = density of effluent (pounds per cubic foot)

$\rho_a$ = density of atmospheric air (pounds per cubic foot)

$g$ = acceleration due to gravity (feet per second$^2$)

$\bar{u}$ = mean horizontal wind speed (feet per second)

## CONCAWE PLUME RISE FORMULA

$$\Delta h = 0.175 \left[ \frac{Q_H^{1/2}}{\bar{u}^{3/4}} \right]$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (meters)

$\bar{u}$ = mean horizontal wind speed (meters per second)

$Q_H$ = heat emission (calories per second)

## LUCAS, MOORE, AND SPURR PLUME RISE FORMULA

$$\underline{\text{IF } \frac{d\theta}{dz} > 0}$$

$$\Delta h = \frac{0.7\ \alpha_N}{\bar{u}} \left[ \frac{Q_N}{G_N} \right]^{1/4}$$

$$\underline{\text{IF } \frac{d\theta}{dz} \leq 0}$$

$$\Delta h = \alpha_N \left[ \frac{Q_N{}^{1/4}}{\bar{u}} \right]$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (feet)

$\alpha_N$ = stack height factor (dimensionless)

$\alpha_N$ = 4,500 for $H_s$ = 200 feet

5,000 = 300 feet

5,500 $\geq$ 400 feet

$\bar{u}$ = mean horizontal wind speed (feet per second)

$Q_N$ = heat emission (megawatts)

$G_N$ = stability parameter = $\frac{108\ \frac{d\theta}{dz}}{\bar{u}^2}$ (dimensionless)

$\frac{d\theta}{dz}$ = change of potential temperature with height (°K per 1,000 feet)

## OPTIMIZED LUCAS, MOORE, AND SPURR PLUME RISE FORMULA

$$\underline{\text{IF } \frac{d\theta}{dz} > 0}$$

$$\Delta h = \frac{(0.7)(5500)}{\bar{u}} \left[ \frac{Q_N}{G_N} \right]^{.22}$$

$$\underline{\text{IF } \frac{d\theta}{dz} \leq 0}$$

$$\Delta h = \frac{(5500)\ Q_N{}^{.20}}{\bar{u}}$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (feet)

$Q_N$ = heat emission (megawatts)

$G_N$ = stability parameter = $\frac{108\ \frac{d\theta}{dz}}{\bar{u}^2}$ (dimensionless)

$\bar{u}$ = mean horizontal wind speed (feet per second)

$\frac{d\theta}{dz}$ = change of potential temperature with height (°K per 1,000 feet)

## OPTIMIZED CONCAWE PLUME RISE FORMULA

$$\Delta h = 0.414 \left[ \frac{Q_H^{.444}}{\bar{u}^{.694}} \right]$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (meters)

$Q_H$ = heat emission (calories per second)

$\bar{u}$ = mean horizontal wind speed (meters per second)

## OPTIMIZED CSANADY PLUME RISE FORMULA

$$\Delta h = C \left( \frac{F}{\bar{u}^3} \right)^{.27}$$

where:

$\Delta h$ = predicted rise of the plume above the stack top (meters)

C = stability coefficient (dimensionless)

F = flux due to buoyancy and momentum = $g\ V_s r^2 \left( \frac{\Delta T}{T_a} \right)$ (meters$^4$ per second$^3$)

g = acceleration due to gravity (meters per second$^2$)

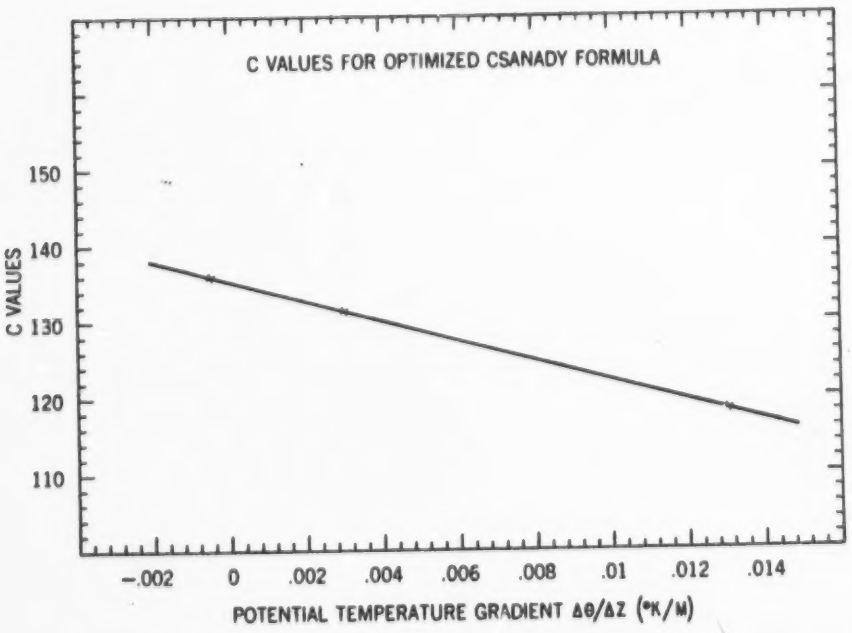
$V_s$ = stack gas exit velocity (meters per second)

r = stack exit radius (meters)

$\Delta T$ = temperature difference between exit stack gas and ambient air (°K)

$T_a$ = ambient air temperature (°K)

$\bar{u}$ = mean horizontal wind speed (meters per second)



## NOMENCLATURE

| Symbol | | System of Units |
|---|---|---|
| B | A value ranging from 1 at zero stack spacing to 0 at approximately 3,000-foot stack spacing | dimensionless |
| b | Buoyant acceleration at top of stack = $g \frac{\rho_a - \rho}{\rho}$ | ft./sec$^2$ |
| C | Stability coefficient | dimensionless |
| d | Stack exit diameter | m. |
| D | Difference between ambient temperature and stack gas temperature at stack top | °K |
| e | Napierian base = 2.71828 | dimensionless |
| F | Flux due to buoyancy and momentum = $g\ V_s r^2 \frac{\Delta T}{T}$ or $V_s r^2 b$ | m.$^4$/sec.$^3$ or ft.$^4$/sec.$^3$ |
| g | Acceleration due to gravity | m./sec.$^2$ or ft./sec.$^2$ |
| G | Change of potential temperature with height from stack top to plume top | °K/ft. |
| $G_N$ | Stability parameter = $\frac{108 \frac{d\theta}{dz}}{\overline{u}^2}$ | dimensionless |
| $H_s$ | Height of stack | ft. |
| $\Delta h$ | Rise of the plume above the stack top | m. or ft. |
| J | $\frac{\overline{u}^2}{(Q\ V_s)^{1/2}} \left[ 0.43 \left( \frac{T_1}{gG} \right)^{1/2} - 0.28 \frac{V_s\ T_1}{gD} \right] + 1$ | dimensionless |
| $\ell$ | $\frac{F}{\overline{u}^3}$ | ft. |
| ln | Logarithm to the base e | dimensionless |
| n | Number of stacks | dimensionless |
| Q | Stack gas emission rate converted to temperature $T_1$ | m.$^3$/sec. or ft.$^3$/sec. |
| $Q_H$ | Heat emission | cal./sec. |

## NOMENCLATURE (continued)

| Symbol | | System of Units |
|---|---|---|
| $Q_N$ | Heat emission | mw |
| r | Stack exit radius | m. or ft. |
| T | Ambient air temperature | °K |
| $T_a$ | Ambient air temperature | °K |
| $T_i$ | Temperature at which density of flue gases is equal to that of the atmosphere | °K |
| $T_s$ | Absolute temperature of stack gas | °K |
| $\Delta T$ | Temperature difference between exit stack gas and ambient air | °K |
| $\bar{u}_4$ | Mean horizontal wind speed at stack top | m./sec. |
| $\bar{u}_3$ | Mean horizontal wind speed at plume bottom | m./sec. |
| $\bar{u}_2$ | Mean horizontal wind speed at plume top | m./sec. |
| $\bar{u}_1$ | Mean horizontal wind speed at plume centerline | m./sec. |
| $\bar{u}$ | Mean horizontal wind speed between stack top and plume top | m./sec. or ft./sec. |
| $V_s$ | Stack gas exit velocity | m./sec. or ft./sec. |
| x | Distance downwind from stack | ft. |
| $x_i$ | Distance downwind from stack where the plume levels off | ft. |
| z | Predicted rise of the plume above the stack top for a given x | m. or ft. |
| $\alpha_N$ | Stack height factor | dimensionless |
| $\theta$ | Plume angle off the line of stacks | degrees |
| $\rho$ | Density of effluent | lbs./ft.$^3$ |
| $\rho_a$ | Density of atmospheric air | lbs./ft.$^3$ |
| $\frac{d\theta}{dz}$ or $\frac{\Delta\theta}{\Delta z}$ | Change of potential temperature with height | °K/100 m. or °K/1,000 ft. |